
1. Executive Summary

1.1 Introduction

The NASA/Marshall Space Flight Center (MSFC)/National Space Science and Technology Center (NSSTC), on behalf of its partner institutions is pleased to submit the revised proposal entitled, “The ALTUS Cumulus Electrification Study (ACES): Investigation of Thunderstorms Using Combined UAV and Ground-based Measurement Systems.”

This proposal is submitted in response to the Uninhabited Aerial Vehicle (UAV)-based Science Demonstration Program (UAVSDP), NASA Research Announcement (NRA) NRA-00-OES-02. The goals of this NRA, which are all addressed by ACES, are to:

- Conduct high-quality basic or applied research that takes advantage of unique capabilities of UAV platforms
- Demonstrate the utility and reliability of UAVs for Earth science and applications observations
- Build confidence in UAV platforms through scientifically useful UAV-based demonstrations.

The ACES team is comprised of scientists at the NASA/MSFC/NSSTC and NASA Goddard Space Flight Center (GSFC) partnered with General Atomic–Aeronautical Systems, Inc. (GA–ASI) and IDEA, LLC. The ACES team, led by the Principal Investigator (PI) Dr. Richard Blakeslee, bring considerable experience to the proposed effort, including aircraft operations (GA–ASI); sensor development; and thunderstorm and other science investigations using aircraft, spacecraft, and rocket platforms. This combined investigator experience makes us a very unique team in terms of developing and successfully flying a payload that will meet even the near-term science and demonstration objectives of the UAVSDP. Our combined experience means that the ACES team can deploy instruments that possess substantial heritage, are of low risk, and can be successfully delivered in the required time. ACES, with its first campaign planned for the summer 2002 timeframe, will quickly demonstrate the usefulness of UAVs for Earth science and applications observations.

1.2 Mission Summary

1.2.1 Investigation Concept

The UAV represents an exciting new technology that can contribute in significant and unique ways to lightning and storm observations. In turn, these measurements can be linked to global scale processes (e.g., global water

and energy cycle, climate variability and prediction, atmospheric chemistry) to provide an improved understanding of the total Earth system.

We have chosen the ALTUS II aircraft produced by GA–ASI for the ACES investigation. The decision to select GA–ASI as the partner was based on a number of factors including the maturity level of the ALTUS aircraft, its performance capabilities and proven flight record, and the successful integration and flight of the ACES payload on ALTUS in September 2000 under a Small Business Innovation Research (SBIR) activity with IDEA managed by one of the Co-Investigators (Co-Is), Dr. R. Goldberg.

We propose to fly ALTUS as a component of a currently funded field experiment. That field experiment, in the vicinity of NASA Kennedy Space Center (KSC), is being conducted to both validate the Tropical Rainfall Measurement Mission (TRMM) satellite measurements, and investigate lightning activity and its relationship to storm morphology. The ACES payload, already developed and flown on ALTUS, includes several electrical, magnetic, and optical sensors to remotely characterize the lightning activity and the electrical environment within and around thunderstorms.

ACES will contribute important electrical and optical measurements not available from other sources. Also, the high-altitude vantage point of the UAV observing platform offers a “cloud top” perspective especially useful for the validation study. In turn, the ground-based experiment will enable the UAV measurements to be more completely interpreted and evaluated in the context of the thunderstorm structure, evolution, and environment. Together, the UAV and ground-based observations will advance the application of global space-based lightning measurements (which are relatively easy to make) toward a better understanding of the Earth system.

1.2.2 Key Science

Three important science objectives will be simultaneously addressed by this UAV investigation: (1) Lightning Imaging Sensor (LIS) validation, (2) lightning-storm relationships, and (3) storm electric budget. The validation effort will provide detailed characterization of lightning type, cloud-top optical energy, and power statistics that is needed to better interpret the global lightning database collected by LIS.

The ALTUS electrical measurements and ancillary ground-based measurements, from the extensive electrical and meteorological observing systems already in place at KSC, will provide detailed information on cloud

properties throughout the thunderstorm life cycle. The relationships between storm electrical and kinematic properties is of particular interest as they might be used to discriminate severe from nonsevere storms. How mesoscale boundaries (e.g., land/ocean) affect the development and evolution of these properties will also be explored.

Finally, ACES electrical measurements will enable us to uniquely address important questions about the electrical budget of thunderstorms, the global electric circuit, and the electrodynamic interaction with the upper atmosphere. The relationship between storm current output and total flash rate will be investigated. Then, using this relationship, the current output from worldwide thunderstorm activity will be estimated from the global observations of lightning now being acquired by the LIS and the Optical Transient Detector (OTD) satellites. This result will provide an independent measure of the current flowing in the global electric circuit.

1.2.3 Demonstration Goals

There are two primary demonstration goals in the ACES project. First, by exploiting the unique capabilities of ALTUS, we will demonstrate the utility and promise of UAV platforms for investigating thunderstorm and other weather phenomena. Slow flight speed, coupled with long endurance and high-altitude flight give the ALTUS aircraft the ability to be maintained continuously near thunderstorms for long periods of time and enable investigations to be conducted over entire storm life cycles. This overcomes the limitations of conventional aircraft that, as a result of much faster flight speeds, provide only a few brief “snapshots” of storm activity sandwiched between long intervening periods with no observations. The ALTUS, with its lower flight speed, can remain within measurement range (i.e., ~5 km) even while making turns. Presently, only the ALTUS has this combination of capabilities, essential for conducting complete storm life cycle investigations (i.e., no gaps). This demonstration goal supports a principal objective of the NRA.

A second goal, supportive of the NRA objectives, is to provide a demonstration of real-time monitoring and control of the UAV science payload and data. During flights, selected instrument output (e.g., electric field) will be sent to the ground via the ALTUS telemetry link enabling us to monitor target storms in real time. In fact, we have proposed to monitor the ambient electric field environment in real time to avoid high electric field (>25 kV/m) regions, and thus reduce to a low probability the threat of incurring a lightning strike to

the aircraft. Output from the ALTUS video camera will also help monitor storm conditions in real time.

1.2.4 Experiment Design

In order to achieve our objectives, we expect to use the ALTUS to observe thunderstorms during two field campaigns in the summer months of 2002 and 2003. It is anticipated that each campaign will last approximately 4 weeks with a goal of performing 8 to 10 UAV flights during each campaign. Each mission will require about 4 to 5 hours on station at altitudes from 40,000 feet to 55,000 feet. For the missions, we will need ALTUS to fly close to, and when possible, above (but never into) thunderstorms using safe operational procedures.

We propose to base the flight operations from Patrick Air Force Base (PAFB), just south of KSC, Florida. At this location, we can take advantage of, and provide close coordination with, the measurements being acquired in central Florida in conjunction with the NASA funded Lightning Imaging Sensor Data Applications Demonstration (LISDAD) experiment. In addition, real-time access and support from ground-based systems already in place, along with standard meteorological data products, will be available to the ACES project. This KSC instrumentation, described in more detail in Section 2.4.3, represents one of the most densely packed and unique suites of operational weather sensors available anywhere in the world. The data provided to ACES will be employed in real time to aid mission planning and execution. During postdeployment, this data will aid in the science analyses and in the education and public outreach lesson plan development.

1.2.5 Technical Implementation

An extensive team member experience base (discussed previously in Section 1.1), technical readiness, and significant heritage characterize the ACES investigation. Technical readiness has been enhanced during the concept definition study by the development of technical plans—Payload Integration Plan, Deployment Plan, Flight Plan, Non-NASA Aircraft Safety Plan, Airspace Management Plan, and Data Analysis, Archival and Distribution Plan. These plans, coupled with corresponding management plans (i.e., Project Control Plan, Project Risk Assessment and Management Plan, and Liability Assessment Plan), provide for an efficient, low-risk technical implementation of the project.

The ACES payload uses existing flight-proven sensors from MSFC and GSFC. The sensors all have a solid heritage derived from previous aircraft or rocket investigations, and thus are very reliable. Previous

platforms include the high-altitude ER-2 and WB-57 aircraft, mid-altitude DC-8 and Citation, and sounding rockets. Since the instruments and data system already exist, there will be minimal development cost and risk associated with the ACES payload. In September 2000, the payload was successfully integrated and flown on the ALTUS at the GA-ASI El Mirage, California flight test center under the aforementioned SBIR activity. These test flights established the physical and functional compatibility of the ACES payload with the ALTUS platform. In addition, ALTUS was found to be an electrically quiet platform ensuring that the proposed thunderstorm measurements can be readily achieved.

The ALTUS also has considerable heritage. The ALTUS is a derivative of the Predator system, now proven with over 22,000 hours of fleet experience worldwide. The ALTUS itself now has flown 70 missions/209 hours without incident. In addition, the ALTUS has demonstrated that it can meet the ACES operational mission requirements to fly altitudes of 40,000–55,000 feet.

1.2.6 Mission Management

The strength of the ACES management approach is the establishment of a Project Office (PO) with experienced personnel, knowledgeable in project management and systems engineering techniques. Through the addition of the ACES PO, an effective systematic approach has been defined using NASA Procedures and Guidelines NPG 7120.5A—NASA Program and Project Management as a guide appropriately tailored to the smaller size and reduced complexity of this project. This approach has: 1) defined, in this proposal, the baseline by which the project will be measured, 2) identified and established proven project control tools to track progress against the baseline, and 3) defined the risk management approach and decision making process to be used in deciding when corrective action is needed to maintain the project goals.

A comprehensive review process, including reviews by an independent review team, has been defined to ensure adequate monitoring and status of the projects progress to baseline plans and project readiness. In addition, adequate technical and programmatic reserves have been budgeted and baselined. Their allocation will be centrally managed by the PM with concurrence of the PI. Finally, just as in the first proposal, the revised management plan is built upon the dedication and personal commitment of each team member, with the full support of their institution.

1.2.7 Education and Public Outreach

Our overall outreach goals are to increase public awareness and inform the public of the purpose and benefits of the ACES project and the NASA Earth Science Enterprise (ESE). The outreach will create a positive image of NASA and the ESE.

We will adopt a three-fold approach to generate effective education and public outreach. First, access to traditional news services with the aid of the MSFC public affairs office (PAO) will create immediate coverage in the form of good press. Second, comprehensive treatments and information about the project will be made available through Web-based outreach. Third, we intend to create an innovative education project designed to inspire the next generation of scientists and engineers through a “hands-on” application employing actual ACES data sets.

1.2.8 Cost Summary

The ACES project can be accomplished with \$4,491K. This project fits within the budget for UAVSDP to fund two or perhaps three proposals. A substantial cost savings is realized since the basic ACES payload already exists and interface verification has been completed under the previous SBIR activity.

Accurate, realistic, and detailed costs were the primary issues throughout the proposal development. A “bottoms up” approach was utilized employing formal tools such as the time-phased WBS dictionary, in conjunction with a detailed project schedule. A strict adherence to the revised proposal cost instructions was attempted. The cost has been reduced since the first proposal to become more competitive—but never at the sake or risk of underestimating the task. Due to the heritage of the payload and basis of cost estimate, a small contingency of 10% is applied. We consider this a conservative number for this project.

The cost estimate from GA-ASI and IDEA are realistic based on their prior SBIR efforts. Their experience and knowledge of the work involved in building and flying this payload has provided a detailed and precise scope of work and cost estimate. In addition, firm-fixed-price-incentive-fee contracts will be used to control cost. The contract with GA-ASI will be established such that we only pay for the hours flown during the campaign. This is significant at \$5,320/hour. The ACES budget includes cost allocation for 64 flight hours per campaign.

The ACES project will highly leverage ground-based and satellite observing facilities (e.g. Doppler radar, LDAR, NLDN, GOES, etc.) at no cost to the project. The collective value of this equipment is considerable; thus, this can be considered an “in-kind” contribution to the project, since no formal accounting system is currently in place to consider this a real cost share.

The Education and Public Outreach budget for ACES is \$167K or 3.7% of the entire ACES budget. This includes equipment, supplies, and consulting fees as well as labor cost for Mr. Greg Cox, Dr. Doug Mach, and a graduate student.

Finally, the second campaign may be descoped at the conclusion of the first campaign if the science and demonstration components of this proposal are satisfactorily achieved. If this occurs, the project cost will be reduced by ~\$1,500K reducing the total project cost to under \$3,000K.

1.3 Changes From the First Proposal

In October 2000, a 90-day concept study was funded to develop a detailed mission implementation plan for ACES. During the study each component of the ACES mission was thoroughly reexamined. This process has led to the incorporation of some important changes into the revised proposal that strengthen the implementation, lower the risk, and improve communication and accountability. Comments and recommendations from the review panels, received during the first proposal debrief and the mid-term review, were carefully considered in this process, as were aircraft and airspace safety concerns. In this section we discuss the key changes that were adopted in the revised proposal.

1.3.1 New Title

The title of the revised proposed investigation is a very obvious change from the original proposal. The study is now called “The ALTUS Cumulus Electrification Study (ACES): Investigation of Thunderstorms using Combined UAV and Ground-based Measurement Systems.” The new title more readily draws attention to the mission’s science and demonstration goals and objectives to study storm and cloud electrification with the ALTUS UAV. In addition, the ACES acronym provides a handle for ease of reference and name recognition to the proposed effort.

1.3.2 Creation of Project Office

The creation of a PO to support the PI in the management of ACES represents an important change in the project management approach. The core of the PO is composed of the Project Manager (PM) and the Lead Systems Engineer (LSE). The PI, PM, and LSE are physically located in the same facility at the NSSTC to provide a cohesive team for timely resolution of project issues.

1.3.3 Contractual Risk Reduction

The ACES project will establish a firm-fixed-price-incentive-award contract with the UAV provider, GA-ASI and also with our Flight Payload Data System (FPDS) provider, IDEA. The GA-ASI contract will establish a fixed price for UAV management, engineering, integration and test, mission planning, mobilization and demobilization, and a fixed hourly rate for flight operations. The IDEA contract will establish a fixed price for the design modifications, fabrication, assembly, and tests of the FPDS and support equipment and support for the ACES payload and UAV integration and test activities. These tasks are well understood following the previous SBIR integration activities of the ACES suite and the ALTUS UAV. The associated cost risks will be low since this type of contract will protect the project and NASA from cost overruns.

This represents a significant and favorable change from the first proposal that utilized a cost-plus contractual approach with GA-ASI and IDEA. Cost-plus contracts are inherently more uncertain and risky since there is no mechanism available to ensure cost containment within the allocated budget and reserve.

1.3.4 Deployment Site

As a result of our concept study analysis, we determined that it would be better, from an airspace management perspective, to conduct the proposed ACES campaigns within the range airspace of KSC, Florida. We will base the flight operations from PAFB just south of KSC. Discussions have been held with the Miami Air Traffic Control (ATC) center to develop procedures for transit to/from the range area. The Joint Planning and Customer Service Office (JPCSO), an interagency office with NASA, Air Force, and State of Florida representation, coordinates access to facilities at PAFB and KSC. We have a letter of commitment and budget from JPCSO to support ACES operations at PAFB and KSC.

This choice of the PAFB deployment site represents a change from the first proposal in which Redstone Arsenal (RSA) Army airfield had been designated as the primary deployment site with PAFB serving as an alternate. At KSC we can conduct missions entirely within range controlled restricted and warning areas, away from densely populated regions along the Florida mainland. This is not possible with RSA thus making it a less suitable location at this time. Other favorable reasons for selecting KSC are that the area of maximum thunderstorm occurrence in the United States is in central Florida near KSC, we can piggy-back on a field program that is already underway at this location (as discussed above), and the existing KSC ground-based network is first class (as discussed above).

1.3.5 Expanded Educational Outreach

We have improved and expanded the educational outreach effort. In the first proposal, ACES education outreach consisted primarily in supporting an atmospheric or computer science graduate student who would participate in premission preparations and field deployment, and assist with subsequent data processing, analysis, and research. However, the reviewers commented that while the graduate student support is commendable, it is neither innovative nor likely to impact a large number of people.

In response to these comments, we intend to create an innovative lesson plan package that will bring the ACES project into American classrooms (Section 5.3). Lesson plans will be developed for teachers of mid-elementary, intermediate, and high-school students, based on actual ACES field activities. The lesson plans will help students experience the fun and excitement of NASA research while learning basic concepts of the scientific method and quantitative reasoning. We envision that the lesson plans will result in a significant long-term impact and value to NASA by influencing and inspiring the next generation of scientists and engineers.

1.3.6 Changes in Key Personnel

Changes in key personnel from the original proposal include the designation of a PM and LSE. These changes were brought about with the addition of the PO discussed above. Also, in October 2000, Dr. Tomo-o Ushio, a NSSTC Co-I, accepted a university appointment in Japan and will no longer participate in the project. Dr.'s. Richard Blakeslee and Doug Mach will assume Dr. Ushio's responsibility for the electric field change sensor. Both have extensive field experience using and interpreting data from this instrument.

1.4 Resolution of Issues and Concerns

This section addresses how specific weaknesses and concerns identified in the original proposal have been resolved. We have adopted a *Comment* and *Response* format that best reflects the way the issues and concerns were presented in the proposal evaluation.

Comment: Safety was not addressed. Is GA-ASI aware that they are flying in a thunderstorm?

Response: Safety has been extensively addressed in the revised proposal. It is discussed in the Flight Plan, Airspace Management Plan, Non-NASA Aircraft Safety Plan, and elsewhere. Safety issues are important factors in the Airworthiness Flight Safety Review Board (AFSRB), Flight Readiness Review (FRR), and Deployment Readiness Review (DRR). In addition, we have specifically addressed safety issues regarding avoidance of lightning strikes (Section 3.3.2.1), avoidance of turbulence (Section 3.3.2.2) and general flight safety (Sections 3.4 Non-NASA Aircraft Safety Plan, and 3.5 Airspace Management Plan). It is important to note, and this can not be overemphasized, **we will NOT be flying the ALTUS into thunderstorms**. We will fly either over or around thunderstorms, but not into them. Conservative standoff distances (~5 km) have been selected based on extensive aircraft penetration data. This will reduce the risk of turbulence or lightning strikes to the aircraft to very low levels.

Comment: Airspace management discussion very generic, and no discussion of FAA requirements.

Response: This has been corrected in the revised proposal. In particular, the Airspace Management Plan (Section 3.5) extensively discusses airspace management as it relates to deployment at PAFB and KSC. Discussions with the FAA have been initiated and are discussed in Section 3.5.2.

Comment: Risk management discussed but only in the context of having designed the mission to minimize risk.

Response: A more complete risk management process has been developed during the concept study and is discussed in Sections 2.3.6 Low Level of Risk, 3.1.2 Issues and Concerns of the Instrument Team and UAV Provider, 3.3.2.1 Avoidance of Lightning, 3.3.2.2 Avoidance of Turbulence, 3.3.3.2 Flight Planning Process, 3.4.1 NASA Safety Review Process for UAV, 3.4.3 Airworthiness of

Aircraft, 3.4.7 System Hazards, 3.5 Airspace Management Plan, and 4.5 Project Risk Assessment and Management Plan.

Comment: PAFB listed as a deployment site, but no commitment from them.

Response: We now have a letter of commitment and budget from JPCSO, an interagency office that coordinates access to facilities at PAFB and KSC.

Comment: Is ALTUS overkill? Only 20 lb of payload will be carried as compared to a capacity for 330 lb.

Response: The 20-lb weight was incorrectly derived from the weight of the electric field mills only. The actual ACES instrument package weighs 183 lb, which leaves a mass margin of 147 lb.

Comment: It is not clear how the cloud microphysical properties will be measured.

Response: With the WSR-88D and WSR-74C radars we will determine the bulk microphysical properties of the target clouds (cloud-top altitudes, reflectivity profile, maximum reflectivity, vertically integrated liquid, etc.) In addition, the high density of meteorological instrumentation at KSC (wind profilers, rain gauge network, etc.) will provide additional bulk microphysical properties of the target clouds. We will then track the development and evolution of these properties and relate them to the lightning and electrification.

Comment: The Doppler radar network, while clearly useful, is less central to the proposed science objectives.

Response: We will use the radars in the study area to determine the bulk microphysical properties of our study targets. In addition, we will use the radars in real-time operation to vector the ALTUS in the vicinity of storm clouds, maintaining safe standoff distances from the thunderstorms.

Comment: While the plan to support a graduate student is commendable, it is not very innovative and the impact is limited primarily to one student.

Response: As noted in Section 1.3.5 and discussed in detail in the Outreach Plan (Section 5.3), we have greatly expanded our educational outreach while maintaining support for a graduate student. In addition, we have defined in more detail our outreach employing more traditional media as well as a Web-based approach.

Comment: The proposal assumes it will be easy to get the public interested and excited about the results of this project. What is that assumption based on and how will that interest benefit NASA ESE?

Response: Our confidence that it will be easy to get the public interested and excited about ACES is bolstered by the excellent response several recent NASA-sponsored programs have received including the TRMM; the Convective and Moisture Experiment (CAMEX); the LIS; the OTD; and the LISDAD—the last three being projects run by the lightning group at the NSSTC/Global Hydrology and Climate Center (GHCC). These highly visible missions have generated an enthusiastic and strong public interest resulting in good publicity for NASA and these programs.

Comment: Thunderstorms and lightning are not topics that are instinctively associated with NASA and remote sensing. How will the project assure the NASA ESE connection is conveyed?

Response: NASA has been involved in thunderstorm and lightning research for at least 30 years. Within the last 5–10 years, with the development and launch of the OTD and the LIS, we have been seeking to communicate to a wider audience the natural association of NASA, remote sensing, thunderstorms, and lightning. Again, Section 5 outlines our approach to conveying the purpose and benefits to NASA and the American public. Now, with assistance from public affairs, the lightning team at MSFC regularly engages in national media contacts. Our research and its relevance to NASA ESE objectives and the nation have regularly been profiled on Good Morning America, the Discovery Channel, the Discovery Science Channel, and the Public Broadcasting System (PBS), as well as through radio and newspaper stories. Even real-time Web interviews have been conducted.

Comment: Who will be doing the work on the Web site? Not just anyone can do a good public outreach Web site.

Response: The MSFC lightning team, NSSTC/Global Hydrology and Climate Center (GHCC) teams, and the NSSTC/Global Hydrology Research Center (GHRC) have developed highly acclaimed and frequently accessed Web sites highlighting science programs, spacecraft, field campaigns, data products and data services. Example sites include:

- www.ghcc.msfc.nasa.gov
- thunder.msfc.nasa.gov
- ghrc.nsstc.nasa.gov
- ghrc.nsstc.nasa.gov/camex3.

We will develop an ACES project Web site patterned after these successful sites. The same resources, personnel, and expertise used to create those sites will be applied to the development of the ACES Web pages. The site will be linked to key sites at the NSSTC (see examples above). The project Web site will include: Mission description, aircraft, and sensors overview; news and events; deployment information; operation plans; browse products; and database access. This site will be created early in the project, support ACES campaign activities, and live on after the mission to provide information and data access.

Comment: Details on the Education and Public Outreach Plan are limited and the source of expertise is not provided.

Response: We now provide many more details about education and public outreach in Section 5, including the source of expertise and as noted in Section 1.3.5, we have greatly expanded our educational outreach. Mr. Greg Cox of the University of Alabama in Huntsville (UAH) Global Learning and Observations to Benefit the Environment (GLOBE) program will provide leadership, guidance, and expertise in the development of a lesson plan package. In addition, we have established contact with some master teachers in our area that will assist us in making the educational outreach effort a success.

1.5 Identified Strengths in Initial Proposal

In the initial proposal, reviewers identified several areas of strength. We have maintained or expanded upon these strengths in the revised proposal. The strengths as identified by the reviewers are listed by general topic.

1.5.1 Science Strengths

“ALTUS is an excellent platform from which to study the evolution of the electrical characteristics of the life cycle of cumulonimbus clouds.”

“Validation of LIS is a valuable undertaking.”

“The science objectives are very tightly focused, so considerable new knowledge on the global circuit, lightning, and atmospheric electricity is likely to emerge.”

“The experiment will result in major improvements in thunderstorm electrical budget and life cycle information.”

1.5.2 Technical Strengths

“Instruments are already developed and are ready to integrate” (and, in fact, the ACES payload has now been flown).

“Clever use of UAV and good UAV justification.”

“Utilizes UAV in conjunction with already funded, ongoing field study on ground.”

“Mission concept is very mature.”

1.5.3 Management Strengths

“This is a good proposal from a very competent PI who has assembled an excellent team.”

“A very well planned, organized, and tasked proposal with a strong and experienced team.”

“Excellent team structure.”

“Responsibilities of PI and Co-Is are well defined.”

1.5.4 Outreach Strengths

“The subject of this proposal, lightning and thunderstorms, is very appealing for education and outreach and should generate interest easily.”

“The plan to include a graduate student is commendable.”

“Good use of the Web for public outreach.”

1.5.5 Cost Strengths

“Cost plan matches schedule of work to be done.”

“The totals are consistent throughout, and the estimates are well documented.”

“Contingencies and descopes are identified.”

2. Science Plan

2.1 Introduction

2.1.1 Background and Relevance

Interest in lightning as a tool for the remote sensing of global change has grown with the recognition that lightning conveys useful information about many atmospheric processes (Davis, 1983; Christian, 1992). For example, since lightning activity is closely linked to storm dynamics and microphysics, it can be related to the global rates, amounts, and distribution of convective precipitation (Goodman, 1986; Goodman, 1990; and Petersen, 1998) and the release and transport of latent heat. The location and distribution of latent heating associated with convection, in turn, influences larger scale atmospheric circulations and weather patterns (Chang, 1999; Goodman, 1986; Goodman, 2000). Williams (1992) hypothesized that global lightning activity may provide a very sensitive measure of temperature change associated with climate variability. Lightning relationships are also sought in atmospheric chemistry concerning the natural production of nitrous oxides and other trace gases (Chameides, 1986; Levy, 1996) and in atmospheric electricity for processes such as the global electric circuit (Blakeslee, 1989; Driscoll, 1993).

In November 1997, the Lightning Imaging Sensor (LIS) was placed in orbit as a component of the Tropical Rainfall Measuring Mission (TRMM) (Christian, 1992). The LIS, in combination with its predecessor, the Optical Transient Detector (OTD) are now providing the first nearly unbiased climatology on the rates, distributions, and variability of lightning activity on a global scale. Furthermore, the combination of sensors on the TRMM satellite is providing a unique opportunity to compare lightning observations to various measurable properties of storms from a variety of regimes around the globe.

NASA's Office of Earth Science is strongly committed to obtaining an improved understanding of the total Earth system and the causes and effects of changes within this system. Lightning and coincident storm observations are highly relevant to this commitment and focus by NASA since, as noted above, these measurements can be connected to processes associated with the global water and energy cycle, climate variability and prediction, and atmospheric chemistry. These categories represent three of the five priority research themes that NASA has identified in its efforts to better understand the Earth.

2.1.2 Mission Concept

NASA demonstrates its commitment to Earth science by actively supporting research and "Ground Validation" (GV) programs. This includes thunderstorm studies, which are needed to establish quantitative relationships and practical algorithms required to interpret and utilize lightning data acquired from both satellite and ground-based lightning detection systems. Furthermore, NASA recognizes the importance of utilizing state-of-the-art measurement systems and platforms in pursuit of new and improved measurements. The Uninhabited Aerial Vehicle (UAV) represents an exciting new technology that can contribute in significant and unique ways to lightning and storm studies.

We propose to fly an instrumented UAV as a component of a currently funded field experiment. That field experiment is being conducted to both validate the TRMM satellite measurements and investigate lightning activity and its relationship to the microphysical and dynamical properties of convection. The ALTUS Cumulus Electrification Study (ACES) payload, already developed and flown under a Small Business Innovation Research (SBIR) activity, includes several electrical, magnetic, and optical sensors to characterize the lightning activity and the electrical environment within and around thunderstorms. Both the slowly varying and transient electrical and optical signals will be acquired.

ACES will contribute important electrical and optical measurements not available from other sources. Also, the high-altitude vantage point of the UAV observing platform offers a "cloud top" perspective especially useful for the validation study. In turn, the ground-based experiment will enable the UAV measurements to be more completely interpreted and evaluated in the context of the thunderstorm structure, evolution, and environment. Together, the UAV and ground-based observations will advance the application of global space-based lightning measurements (which are relatively easy to make) toward a better understanding of the Earth system.

We have chosen the ALTUS II aircraft produced by General Atomics-Aeronautical Systems, Inc. (GA-ASI) for this proposed UAV investigation. The decision to select GA-ASI as the partner was based on a number of factors including the maturity level of the ALTUS aircraft, its performance capabilities and proven flight record, and the successful integration and flight of the ACES payload on ALTUS in September 2000 under the aforementioned SBIR activity managed by one of the Co-Investigators (Co-Is), Dr. R. Goldberg.

In order to achieve our objectives, we expect to use the ALTUS, shown in Figure 2.1, to observe thunderstorms during two field campaigns in the summer months of 2002 and 2003. It is anticipated that each campaign will last approximately 4 weeks with a goal of performing 8 to 10 UAV flights during each campaign. Each mission would require about 4 to 5 hours on station at altitudes from 40,000 feet to 55,000 feet. For the missions, we will need ALTUS to fly close to, and when possible, above thunderstorms (but never into storms) using safe operational procedures.

2.1.3 Advantages of the ALTUS Over Alternate Platforms for Storm Investigations

The performance characteristics of the ALTUS, including some very unique capabilities, make this UAV ideally suited for pursuing the proposed thunderstorm studies. The performance characteristics include high-altitude flight, long-duration missions with long “on station” time, slow flight speed, and quick response time. No other aircraft platform has this combination of capabilities, essential for acquiring complete storm life cycle observations.

High Altitude Flight. In 1999, the ALTUS demonstrated the capability for flight at 55,000 feet for 4 hours and for sustained flight above 50,000 feet for 8 hours. Although reaching these altitudes is not unique to the ALTUS (e.g., the NASA high-altitude ER-2 or WB-57 aircraft can attain higher altitudes), this altitude capability is an absolute requirement for this study. Without the 40,000 to 55,000 feet flight levels, cloud-top perspective storm research would be impossible.

Continuous Observations of Storms. The ALTUS is also capable of long-duration flights. This enhances the



Figure 2.1.—The ALTUS II aircraft shown in flight over the California desert.

probability of successfully engaging thunderstorms within the experimental domain and acquiring scientifically useful data sets. Even more importantly, the ALTUS operates at flight speeds that are considerably slower compared to most research aircraft. The slow cruise speed, coupled with its long endurance provides its most unique and significant capability—*Continuous Observations*. This capability, not available from any other research aircraft, can be used to great advantage for storm research. It is anticipated that the ALTUS could be maintained above or within useful measurement range of a thunderstorm for a long period of time, perhaps throughout its entire life cycle (typically 1–1.5 hours for the “pulse-type” thunderstorms occurring at Kennedy Space Center (KSC) in the summertime). In contrast, the ER-2, flying at ~200 m/s, passes over a similar storm in 1 or 2 minutes. Then it takes about 10 minutes to turn around for another pass, during which time useful storm measurements are lost. Generally, one or two short passes are all that can be expected resulting in only brief “snapshots” of the storm investigated. On the other hand, the ALTUS, cruising at less than one-third the speed of the ER-2, will experience dramatically increased dwell times over the storm. Also, the lower flight speed will enable the UAV to continuously remain in measurement range (i.e., within 5 km) even while making turns.

Rapid Response. Another important feature of the ALTUS system is the rapid response time from a decision to launch the vehicle to takeoff. Once a decision is made to go, the ALTUS can be ready for takeoff in 2 hours. Although a preliminary decision to fly on a given day will be made the previous day based on the forecast and other considerations, having the flexibility to easily adjust the takeoff time is extremely important when investigating airmass thunderstorms (or other weather phenomena).

Reduced Risk to Personnel. Finally, it is worth noting that another unique characteristic of all UAV platforms is that they are “uninhabited”. No pilot and/or passengers are placed at risk during these missions. This is a worthwhile consideration for storm investigations in which an aircraft might inadvertently encounter severe turbulence or other potentially dangerous conditions (e.g., lightning strikes to the airframe).

2.2 Science

ACES addresses three primary science objectives: 1) LIS validation, 2) lightning-storm relationships, and 3) storm electrical budget. Figure 2.2 illustrates the connection between the measurements, enabled science, and NASA ESE science priorities. The proposed UAV validation effort will enable science by providing a detailed

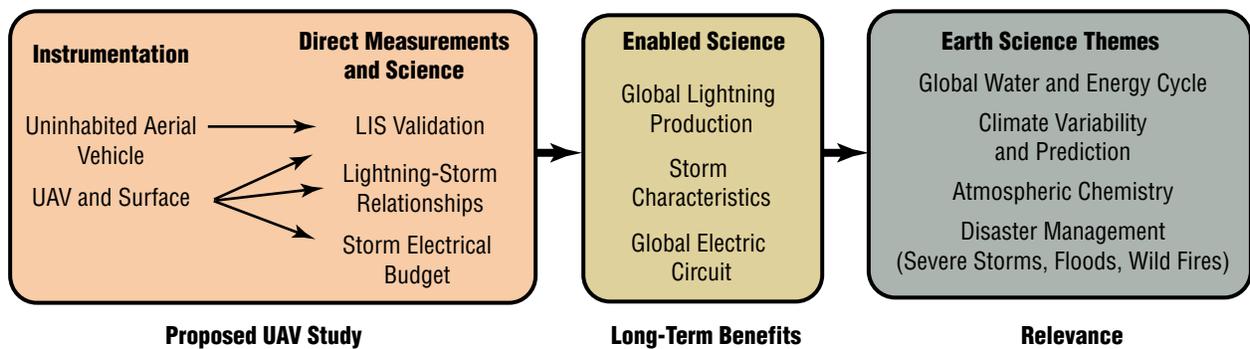


Figure 2.2.—Science traceability matrix showing how the proposed UAV study results enable science that is highly relevant to several NASA’s Earth Science Enterprise science and application themes.

characterization of lightning type, cloud-top optical energy, and power statistics that provides more detailed insight into the process of aggregating LIS optical pulses into flashes, as well as LIS flash detection efficiency for in-cloud lightning versus discharges to ground. This information is needed to better interpret the global lightning database collected by LIS. The near-cloud UAV electrical measurements and ancillary ground-based measurements from electrical (field mill network, LDAR) and meteorological observing systems (mesonet, profilers, Doppler radar) at KSC will provide detailed information on cloud properties throughout the thunderstorm life cycle. The relationship between storm electrical and kinematic properties is of particular interest as they might be used to discriminate severe from nonsevere storms. How these properties change as storms cross mesoscale boundaries is also of great interest. Finally, UAV electrical measurements enable us to uniquely address important questions about the electrical budget of thunderstorms, the global electric circuit, and the electrodynamic interaction with the upper atmosphere.

The UAV measurements provide an uninterrupted depiction of the storm growth and decay life cycle—from the very first indication of electrification to the first lightning through thunderstorm dissipation. The timing of the initial electrification and the complete documentation of total lightning activity provide important validation data for newly developed three-dimensional storm electrification models with explicit (and detailed) microphysics (Mansell, 2000). Such models make explicit forward predictions of the co-evolving microphysics, kinematics, and the total flash rate partitioned into in-cloud and Cloud-to-Ground (CG) lightning components, including flash polarity. The ability of the UAV to stay aloft for an extended period also offers an opportunity to observe convective storms as they transition from multicellular storms into organized mesoscale convective weather systems having well defined convective and stratiform precipitation regions and electrical coupling to the

upper atmosphere. These weather systems and the charging zones in the stratiform region are too horizontally extensive to be adequately sampled by the KSC field mill network and the LDAR lightning mapping system alone. The combined UAV and ground-based observations will provide a necessary measurement set that yields more physically realistic cloud models, which in turn can be expected to benefit the forthcoming higher-resolution research and operational mesoscale forecast models.

The connection of the measurements to the enabled science and thus to NASA’s science themes, depicted in Figure 2.2, is clear. Storms are the fundamental elements of the global water and energy cycle and the agents of severe weather, flash floods, and wild fire initiation. The unique set of observations afforded by the ability of the UAV to continuously observe storms for extended periods of time will improve our understanding of the process physics and lead to improved models of individual thunderstorms and convective weather systems.

2.2.1 Lightning-Storm Relationships

Both theory and observations show that the processes that lead to the production of lightning are tightly controlled by the cloud updraft and the formation of ice (Baker, 1995; Dye, 1986). Lightning initiates soon after the onset of strong convection, after significant cloud mass and ice have formed in the upper regions of the thunderstorm. It is this physical coupling that enables us to use lightning to study strong convection and ice development. Developing these lightning relationships is important because lightning is often easier to measure than most convective parameters and lightning measurements can be easily made from space.

A good example of the strong coupling that exists between convection and lightning is shown in Figure 2.3. This highly-resolved time series of lightning, cloud mass, and dynamics in figure 2.3 shows that *total lightning* i.e., IntraCloud (IC) + CG coincides with the vertical

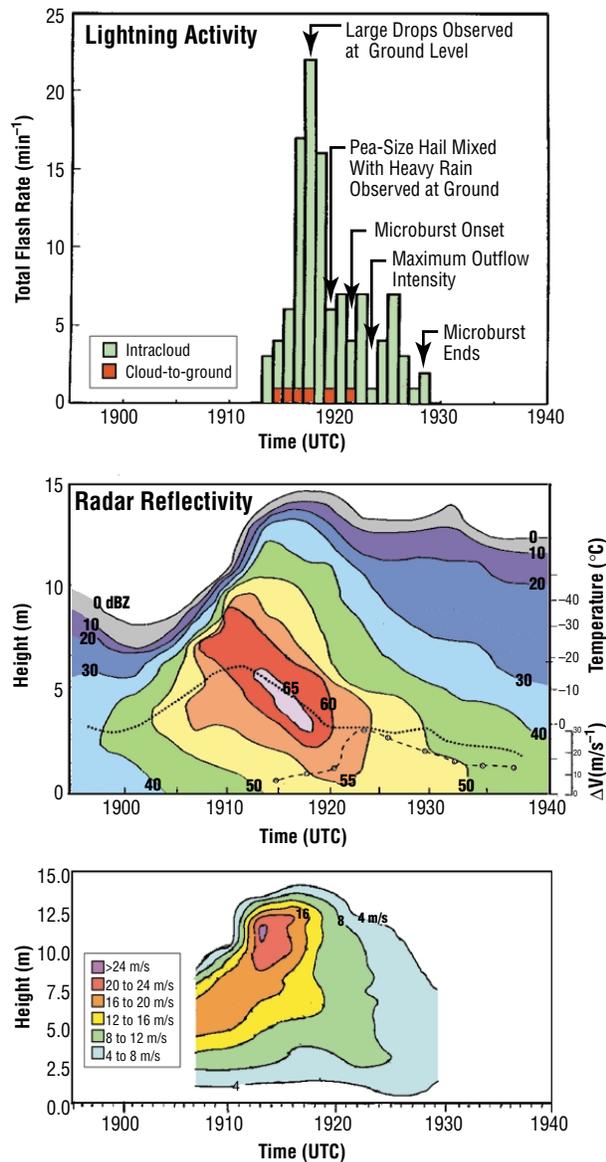


Figure 2.3.—The lightning, radar echo, and vertical velocity development for an airmass or “pulse-type” summer storm (after Goodman, 1989; Kingsmill, 1991).

development of the convective core and precipitation mass aloft. The lightning activity begins when the cloud is developing vertically, shortly after the first radar indications of frozen precipitation at a height of 6–7 km (Goodman, 1989) and flash rate increases as the updraft intensifies. The flash rate quickly diminishes as mass loading initiates the downdraft and the precipitation core descends to the surface.

These data were collected from an earlier, large, coordinated field program in the North Alabama region. The anomalously large fraction of IC lightning shown here

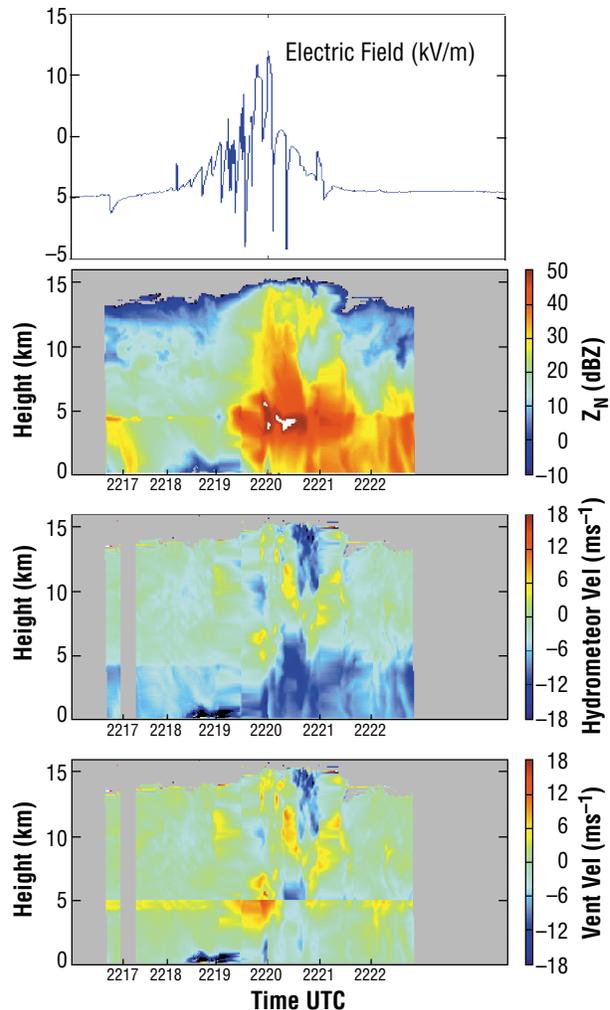


Figure 2.4.—Coincident electric field and radar ER-2 observations collected over a Florida thunderstorm on Aug. 15, 1998. The large electric fields and frequent lightning are well correlated with the regions of strong updrafts (and also cloud ice aloft).

has also been observed in the “pulse-type” severe and tornadic storms in Florida (Goodman, 1999; Williams, 1999). We note that high time-resolution measurements of total lightning are necessary to see this relationship.

Figure 2.4 is an example of the electric field and radar reflectivity acquired during an ER-2 overflight of a Florida thunderstorm. Again, basic meteorology tells us that a relationship should exist between lightning flash rate and updraft strength, perhaps above some threshold value (Zipser, 1994), however, there presently exists no way to measure updraft strength on a global scale. Since it is easy to measure lightning flash rate globally, we are very interested in quantifying this relationship. Measurements from the ALTUS aircraft will improve

upon these in several ways. First, as noted in the introduction, the slow flight speed of the ALTUS will increase the dwell time over a storm by at least a factor of three. Second, it may be possible to keep the aircraft within measurement range for the entire 1–1.5-hour life cycle of the storm. Thus, with the UAV observations, entire case studies, such as the time-series example presented in Figure 2.3, can be assembled with aircraft data; something that, heretofore, has not been possible.

While it is widely recognized that strong relationships exist between lightning, updraft strength, ice mass aloft, storm height, and precipitable water the observed connections, as illustrated in Figures 2.3 and 2.4 remain essentially qualitative. The multiparameter data sets we propose to collect with the UAV, ground based, and satellite-based (e.g., TRMM, GOES, DMSP SSM/I) instrumentation will further contribute to the effort to develop a functional description between lightning and many of the above parameters. Scatter plots of lightning rates versus the cloud parameters will help identify and statistically validate relationships between these parameters.

We will also test scaling relationships (Vonnegut, 1963; Williams, 1985; Price, 1992; Baker, 1995) between total lightning and cloud-top heights during this UAV study. It has been suggested (Williams, 1985) that lightning rates should be proportional to the fifth power of cloud-top heights. However, more recently Baker (1995) used a simple numerical model to suggest that the lightning rates are more proportional to the first power of the cloud parameters such as cloud width and radar reflectivity.

2.2.2 Lightning Imaging Sensor Validation

The large sampling afforded by long-duration UAV flights is critical for improved suborbital validation of the NASA LIS and OTD satellites. The Detection Efficiency (DE) of these instruments varies with their minimum detectable radiance (a function of location in their Charge Coupled Device (CCD) array, off-boresight angle, and background radiance). Prelaunch estimates of this detection efficiency were based on a small sample of optical pulse measurements associated with less than 350 lightning discharges collected by the NASA U–2 aircraft in the early 1980s (Christian, 1987; Goodman, 1988; Koshak, 2000). In addition, only 25 of the earlier lightning measurements were confirmed as CG discharges. The Optical Pulse Sensor (OPS) in these flights had higher sensitivity than the OTD and comparable sensitivity to the LIS. Therefore, an examination of the OPS probability distribution function of pulse radiances

directly yielded an estimate of OTD/LIS detection efficiency as a function of minimum detectable radiance.

This approach has been repeated using the most sensitive LIS observations (i.e., the fourth CCD subquadrant, Q4, at night) as an analogue to the previously obtained U–2 radiance spectra. In other words, the detection efficiencies *relative to the LIS Q4 night* are computed in the same way that detection efficiencies *relative to the U–2 OPS* were computed. The relative detection efficiencies (as a function of sensor threshold radiance) are shown in Figure 2.5. Clearly, there is disagreement between the LIS-based and U–2-based estimates. When constructing this curve, it was observed that the LIS-relative DE predictions were very sensitive to the number of flashes in the sample. For sample sizes comparable to the small U–2 data set, the variance in the predictions was high (i.e., the discrepancies in Figure 2.5 are, thus, likely due to the small U–2 sample size).

The ALTUS, having a slow flight speed, and thereby able to stay in continual proximity to a storm, will be better

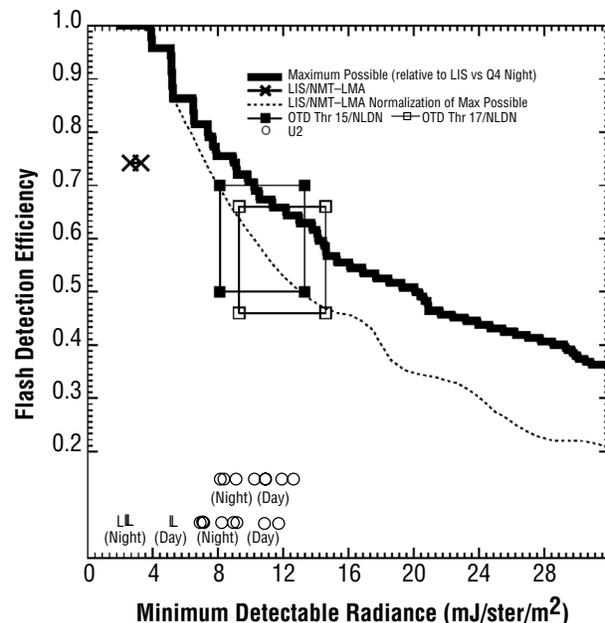


Figure 2.5.—Maximum possible lightning flash DE estimated from the small-sample U–2 flights (dashed line) and from the most sensitive LIS CCD subquadrant at night. Differences in the curves appear due to the much larger sample size of LIS data. Absolute DE estimates based on satellite-surface sensor validation studies are overlaid (crosses and boxes). Actual LIS (L) and OTD (O) CCD subquadrant sensitivities for night and day conditions are indicated at bottom.

able than the U-2 to acquire a large sample of optical pulse measurements. These pulse measurements from a calibrated OPS instrument with a well-established sensitivity, better than LIS, are critical for suborbital confirmation and validation of the bootstrapped LIS-relative predictions (which should be treated with caution, as they were necessarily derived from a noise-filtered LIS data set). The fact that these curves are not concave down at low radiances (Figure 2.5) also raises the question of how much of the true population lies below the earlier U-2 and LIS minimum detectable radiances. This is crucial for knowledge of whether our absolute DE estimates are reasonable.

By combining these measurements with independent measures of electrical *energetics* collected from the ALTUS measurements (see Section 2.2.3), we will also be able to determine how *relevant* are the population of low-radiance pulses and flashes. Since observations of flash rate are coupled to overall storm electrical energetics and microphysical/dynamical properties through these energetics, it is important to know whether missed flashes, at or below the low end of the radiance spectrum, are relevant for OTD, LIS, or future satellite sensor scientific goals. This knowledge will feed back into whether additional engineering improvements are required to improve satellite sensor sensitivity (which, due to the large number of dim pulses, comes at a significant cost in total data bandwidth).

Finally, the opportunity for direct validation of the LIS sensor through coincident storm measurements may present itself during this program. This is not presented as a key validation objective in this proposal since it is readily recognized that such opportunities will undoubtedly be small. Nonetheless, any coincident storm measurements between the UAV and LIS will be quite valuable.

2.2.3 Global Electric Circuit and Storm Electrical Budget

Over the past 100 years, progress toward understanding the global electric circuit has been made at a very slow pace. At the early part of this century, researchers determined that thunderstorms were responsible for the currents that circulate in the Earth's atmosphere between the highly conductive ionosphere and the surface of the Earth (*Wilson, 1920*). This discovery eventually led to the modern concept of the global electric circuit, as depicted in Figure 2.6. However, the details that explain how thunderstorms contribute current to the global electric circuit have remained elusive, and the hypotheses that seek to explain a thunderstorm's role in the global

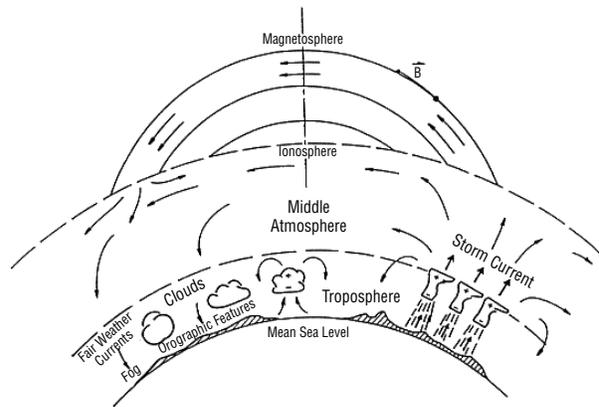


Figure 2.6.—Modern concept of the global electric circuit. Nonetheless, details about the sources of current within the storms contributing to the circuit need to be better elucidated.

electric circuit have not always been consistent with measurements. One of the goals of collecting electrical measurements over thunderstorms with the ALTUS is to better understand the processes involved in sustaining the global electric circuit.

(a) Lightning/Current Relationships. Thunderstorms around the globe must collectively supply 1,000 amperes of upward current to the global electric circuit in order to balance the downward flow of the fair-weather current. As shown in Figure 2.7 (a) and (b), *Whipple (1936)* demonstrated that diurnal variations in point discharge measurements from the Carnegie measurements were well correlated in phase but not in amplitude with distribution and timing of thunderstorms around the globe. More recently, the diurnal variation of global lightning frequency, computed from OTD observations (*Blakeslee, 1999*) was found to be in good agreement to the earlier estimate of global thunderstorm occurrence as shown in Figure 2.7 (c). The amplitude variations about the mean value of thunderstorms and lightning are considerably greater than the Carnegie curve (i.e., 35% versus 15%, respectively). The reason for this discrepancy is still not well understood.

For many years it was widely believed that CG lightning must be the primary source of the 1,000 amperes continuously flowing in the global electric circuit. It seemed plausible that each CG discharge could transfer 10 C of negative charge to ground at a global rate of 100 flashes/s (*Brooks, 1925*). However, recent satellite measurements from OTD indicate the global total flash rate (IC and CG) averages between 40–50 flashes/s, while the global CG flash rate is only between 10–15 flashes/s. This new information

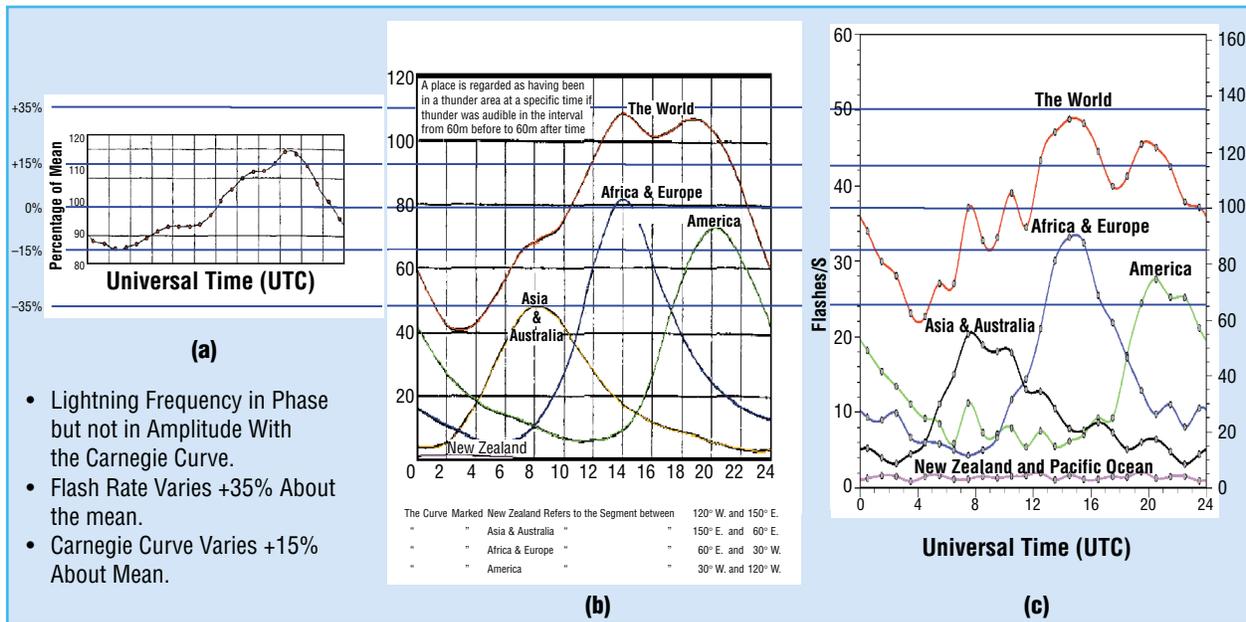


Figure 2.7.—(a) The diurnal variation of the fair-weather oceanic potential gradient commonly referred to as the “Carnegie curve” and (b) the diurnal global thunderstorm occurrence and the corresponding contributions from America (30° W to 120° W), Africa and Europe (60° E to 30° W), Asia and Australia (150° E to 60° E), and New Zealand and the Pacific Ocean (120° W to 150° E) derived from thunderday statistics (*Whipple, 1936*). (c) the global lightning frequency derived from OTD data plotted as in (b). Note the good agreement with (b).

suggests that CG lightning can only be responsible for a fraction of the 1,000 amperes required to maintain the current flow in the global circuit. As a result, some parts of the existing hypotheses are in the process of being revised.

Recently, *Williams (1993)* has suggested that the primary source of current to the global electric circuit is point discharge (corona currents). They hypothesized that the amplitude and duration of the local point discharge currents may account for the differences in the diurnal amplitude variation of the global flash rate compared to the Carnegie curve noted earlier. While this hypothesis may turn out to be important, another possible explanation is that a highly nonlinear lightning/current relationship is operating.

Intense displacement currents following lightning discharges (*Blakeslee, 1989*) may also add a large contribution to the global currents. For approximately 10–30 s following a discharge, displacement currents exceed conduction currents. Albeit impulsive in nature, when averaged over the thunderstorm lifetime, they may contribute significant current to the global electric circuit. The magnetic search coil antenna and magnetometer will make definitive measurements of these displacement currents (i.e., dB/dt) from a thunderstorm, and their contribution to the global circuit can be assessed.

We propose to use the ALTUS electrical observations to investigate the upward directed current flowing from thunderstorms. We will focus this analysis on obtaining a relationship between storm current output and total flash rate. Then, using this relationship, the current output from worldwide thunderstorm activity will be estimated from the global observations of lightning now being acquired by the LIS and OTD satellites. This result will provide an independent measure of the current flowing in the global electric circuit. In addition, it will help determine if it is still possible to understand the Carnegie curve variations using a relation based on global lightning activity (e.g., space-based measurements of lightning).

(b) Measure and Compare DC to AC Power Over Thunderstorm Lifetime. Given the measurement of the current and the direct current (DC) electric field, a determination of the DC power of a thunderstorm is easily obtained. This estimate can be compared to alternating current (AC) power output of a thunderstorm derived from Poynting Flux ($E \times B$) measurements, where E is the vector electric field and B is the vector magnetic field. The AC power is expected to peak just after a lightning stroke. The overall RMS power over the lifetime of a thunderstorm may be very large—even exceeding the DC power.

The most significant displacement currents are created in the “postdischarge” period following a CG stroke. These currents have amplitudes comparable to the quasi-DC conduction current contribution (Blakeslee, 1989). Models of the global atmospheric circuit have usually only included contributions from quasi-DC conduction currents from thunderstorms. The AC contribution to the global circuit, in the form of postdischarge displacement currents, has not been quantified. Yet, these transient events may contribute substantial power to the global circuit. The ALTUS measurements will allow us to explore this possibility, with magnetic sensors obtaining displacement currents, $d\mathbf{B}/dt$, and the combined electric and magnetic measurements yielding power flux, $\mathbf{E} \times \mathbf{B}$. The time-averaged contribution from the AC power can then be added to global models, and in particular, determine the overall AC power (displacement current) contribution to the global electric circuit in tandem with the DC power.

This study has not been done before because it requires measurements from a platform that is moving with the storm system over the thunderstorm life cycle. The ALTUS is perfect for this study since it can trail a thunderstorm over its lifetime to obtain estimates of both the DC and AC power produced by the storm’s electrical generator and associated lightning discharges.

(c) Storm Current Budget and Test of the Convective Charging Mechanism. An opportunity to obtain the current budget in a thunderstorm will present itself if we conduct a field campaign at Patrick Air Force Base (PAFB), Florida. The complete current budget consists in determining the vertically directed currents flowing above, within, and beneath a thundercloud. By determining the current budget, it will be possible to test support for the convective theory (Vonnegut, 1963) of thunderstorm charging since this theory places specific constraints on the expected storm currents.

The LDAR system and electric field mill network at Kennedy Space Center (KSC) will provide total lightning detection (CG and IC), map the locations (x,y,z), and amounts of charge or charge moments neutralized or redistributed by lightning discharges, lightning current estimates, storm electric currents, and cloud charge estimates. The analysis software and expertise have been developed at Marshall Space Flight Center (MSFC) for the analysis and inversion of the KSC LDAR and field mill data needed to support the analysis proposed here. It may also be possible to successfully conduct this experiment in Alabama if estimates of the lightning current can be derived using the LMA and the ALTUS field mills and electric field change sensor.

Driscoll (1992, 1994) showed that the time-averaged upward current, I_{up} , produced by a bipolar thunderstorm with an upper charge center at h' and a lower charge center at h'' can be expressed as

$$I_{up} = (I_G - I_{ic})(1 - e^{-2kh'}) - (I_G - I_{ic} - I_{cg})(1 - e^{-2kh''}) \quad (1)$$

where I_G , I_{ic} , and I_{cg} are the time-averaged values of the generator current, the IC lightning current, and the CG lightning current. The approach will be to determine the thunderstorm charge center locations and the CG and IC lightning currents using the KSC field mill data (ALTUS field mill data may be applied to these inversions as well). At the same time, the ALTUS will measure the time-averaged current flowing above the cloud top. Equation (1) will then be solved for the generator current. Note that in determining the generator current it is not necessary to describe the character of the generator using fundamental variables common in convective and precipitation (Latham, 1981; Williams, 1985) theories. Instead, the nature of the generator is inferred using only a few variables: The cloud-top current, the lightning current and thundercloud charge altitudes, and an empirical estimate of the conductivity (we are not restricted to two levels if our analysis indicates a more complex charge structure necessary).

2.3 Field Campaigns

We propose to base the flight operations from PAFB, just south of KSC, Florida. At this location, we can take advantage of, and provide close coordination with, the measurements being acquired in central Florida in conjunction with the NASA funded Lightning Imaging Sensor Data Applications Demonstration (LISDAD) experiment. In addition, real-time access and support from ground-based systems already in place, along with standard meteorological data products, will be available to the ACES project. This KSC instrumentation, described in more detail in Section 2.4.3, represents one of the most densely packed and unique suites of operational weather sensors available anywhere in the world. The data provided to ACES will be employed in real time to aid mission planning and execution and, during postdeployment in the science analyses and lesson plan development (Section 5.3).

Presently—and this is a change from the first proposal submission—we plan to conduct both of the proposed campaigns in KSC restricted range airspace. Although none of the ACES investigators are stationed in the PAFB/KSC area, several have extensive experience with airborne and ground-based field programs conducted in the KSC vicinity. These experiences will allow us to make the most use of the facilities in the PAFB/KSC area.

In addition, we are familiar with the weather patterns in the PAFB/KSC area.

2.3.1 Mission Requirements

We have proposed to observe thunderstorms during two field campaigns in the summer of 2002 and 2003. As stated earlier, each campaign will last approximately 4 weeks with a goal of completing 8–10 flights per campaign. Since our objective is to acquire thunderstorm electromagnetic measurements over the storm’s lifetime, ALTUS is required to be on station and at altitude (~40,000 to 55,000 feet) anywhere from 1–5 hours. ALTUS also requires about 1.5–2 hours to reach this altitude (and similar time to return). Therefore, in order to intercept the storm’s formative stage, ALTUS will generally be launched prior to the development of much significant storm activity (but in anticipation of this activity based on our best forecast). We anticipate that the typical mission will last 5–8 hours. The ability to prepare ALTUS and crew for a subsequent flight will be a function of the preceding mission duration.

Since the electric fields fall off rapidly with distance due to the dipolar charge structure, it will be necessary to maintain the UAV as close to the storm as possible, usually to within 5 km of the storm edge. When possible, we will vector the UAV directly over the top of the thunderstorm, while maintaining the closest vertical approach to the storm top as possible. ALTUS will also acquire measurements from alongside large storms, when it is unable to clear the cloud tops. Additional details about the ALTUS flight concept for the conduct of mission operations in the KSC area and in the vicinity of thunderstorms are presented in Section 3.3. Safety and hazard avoidance have been paramount in the ACES mission planning and in the development of the Flight Plan, Non-NASA Aircraft Safety Plan(Section 3.4), and Airspace Management Plan (Section 3.5).

2.3.2 Expected Weather

The area of maximum thunderstorm occurrence in the United States is in central Florida near KSC. This activity peaks during the summer months. Table 2.1 shows a climatological monthly frequency of thunderstorms in 3-hour increments at the Shuttle landing facility located near the center of KSC for the 10 years 1983–1992 (Harms, 1998). Not unexpectedly, the greatest frequency of occurrence is in summer afternoons between 12–17 local standard time (LST). The climatological number of thunderstorm days for the KSC area is 12.4 days for June, 15.0 days for July, and 13.4 days for August. This means that on average, there will be thunderstorms every 2–3 days. The ACES field campaign will be

Table 2.1.—Percent of hourly observations of thunderstorms at the KSC Shuttle landing facility (1983–1992) (Harms, 1998).

LST	Apr.	May	June	July	Aug.	Sep.
00–02	1	1	1	1	2	1
03–05			1	1	1	1
06–08			1	1	1	1
09–11			1	1	1	1
12–14	2	2	12	12	13	5
15–17	3	5	15	15	17	7
18–20	1	5	8	8	9	4
21–23	1	2	3	2	4	2

conducted in a continuous 4-week period to take advantage of the summer activity “window.”

Summer thunderstorms in the KSC area are generally of the small air mass “pulse-type” variety. They are usually slow moving with typical lifetimes of 1–1.5 hours or less. The typical dimension of the thunderstorms is around 10 km in diameter with heights around 15 km. Anvils from the thunderstorms are usually 40–50 km in diameter with typical anvil heights of around 12 km. Since synoptic-scale forcing is quite weak in the summer season, the thunderstorm formation is dominated by weak interacting boundaries, often initiated by differential heating and classic seabreeze convergence. The seabreeze storms often develop significant organization along the seabreeze front. Other mechanisms, although weak, can produce boundaries and boundary interactions sufficient to contribute to summer thunderstorm development. These include convective outflows, river and lake breezes, cloud shadow and soil moisture temperature discontinuities, washed out frontal zones/shear lines, and remnants of boundaries from previous day(s) (Roeder, 2000).

2.3.3 Example Flight Patterns

The basic goal of the flight patterns is to stay as close to the thunderstorm of interest for as long as possible. In most cases, it will be desirable to overfly the storm as it initiates, grows, matures, and decays. Occasionally the storm becomes too intense or vertically developed to directly overfly. In that case the ALTUS may be flown around the storm while staying as close to the storm as possible. Turns will be made as quickly and smoothly as possible to maximize the data collection quality.

The primary flight pattern will be the petal as shown in Figure 2.8(a). This pattern will be best for isolated storms that can be overflown. The approach to the storm will be on a vector directly over the center of the storm. The

initial flight path will continue until the aircraft has passed over the storm. As soon as possible after the aircraft clears the storm top, the aircraft executes a sharp (but smooth) turn until it is again on a vector over the storm center. Note that as the storm moves, the pattern will stay constant in the storm frame-of-reference, that is, we want to stay with the storm, not with some set location fixed in relation to the ground. This pattern will continue until the storm has decayed or the aircraft is vectored to another target.

If the petal flight pattern is not appropriate for the storm situation, the next desirable flight pattern is called the racetrack, shown in Figure 2.8(b). This pattern will be most appropriate for lines of thunderstorms or storms with significant anvils. The approach to the storm is along a vector in line with the storm center or storms centerline. Once the aircraft has cleared the storm (or reached the end of the storm line or anvil), the aircraft executes a $90^\circ/270^\circ$ turn set to return it to the same storm relative heading as on the previous vector, only in the opposite direction. This pattern continues until the storm has decayed or the aircraft is vectored to another target.

If the storm is too tall or severe for direct overflights, the polygon pattern, Figure 2.8(c), will be the next best choice. The approach pattern will be to make the closest approach to the storm as conditions allow. Once this closest approach is made, the aircraft is to make a series of glancing approaches to the storm. The occasional, small turns are to be made as quickly and as smoothly as possible so that the maximum time is spent on straight and level flight. This pattern continues until the storm has decayed or the aircraft is vectored to another target.

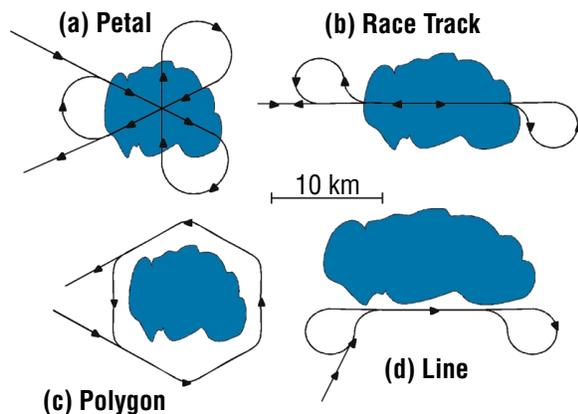


Figure 2.8.—Examples of flight patterns that will be used during the ALTUS missions.

The final flight track, Figure 2.8 (d) is called the line. It is for cases where there is a line of storms that are too severe or tall to overfly. The aircraft is to approach the storm as if it were going to overfly or penetrate the first storm in the line. At the distance of closest approach, the aircraft is to turn and fly straight and level, parallel with the front face of the storm system. After the UAV passes the storm system, it will execute a $90^\circ/270^\circ$ turn set away from the storm to bring the aircraft back along the initial storm relative flight line only now in the opposite direction. The actual distance to the storm edge will be determined by the storm type and severity. This pattern will continue until the storm system decays, moves out of range, or the aircraft is vectored to another target.

Figure 2.9 provides two examples of how storms might be flown using actual KSC area radar data. The figure shows WSR-88D images of a summer thunderstorm over the KSC restricted area. In the first image, labeled “15:01”, the storm is too severe to overfly. In this case, we will use the line flight pattern to study the storm. Note that the ALTUS flight path is always over the KSC restricted area or the ocean. By the time of the second image, labeled “15:21”, the storm has moved over the ocean and decayed enough to overfly. Since the storm has developed an anvil, we will use the racetrack flight pattern. Depending on the circumstances, we might also want to use the petal pattern when the cloud top allows overflights. In any case, we will use whatever pattern keeps us within the KSC restricted area or over the ocean and is able to meet the science goals.

2.3.4 Alternate Deployment Site

An alternate deployment site is the Redstone Arsenal (RSA) Army airfield near Huntsville, AL. Scientifically, RSA offers ground-based measurement systems and observing opportunities similar to those available at PAFB. These systems and a concurrent field experiment (a successor to LISDAD being conducted in Northern Alabama) will provide in-cloud mapping of lightning channels from an advanced 10-station LMA, ground strike locations from the National Lightning Detection Network (NLDN), single/multiple Doppler radar coverage, wind profiler measurements, and forecast support. The area is also home for the National Space Science Technology Center (NSSTC)/Global Hydrology and Climate Center (GHCC). Since the Principal Investigator (PI), one Co-I, the project manager (PM) and several support people are stationed at the NSSTC, they are familiar with both the facilities at RSA and the weather patterns in Northern Alabama.

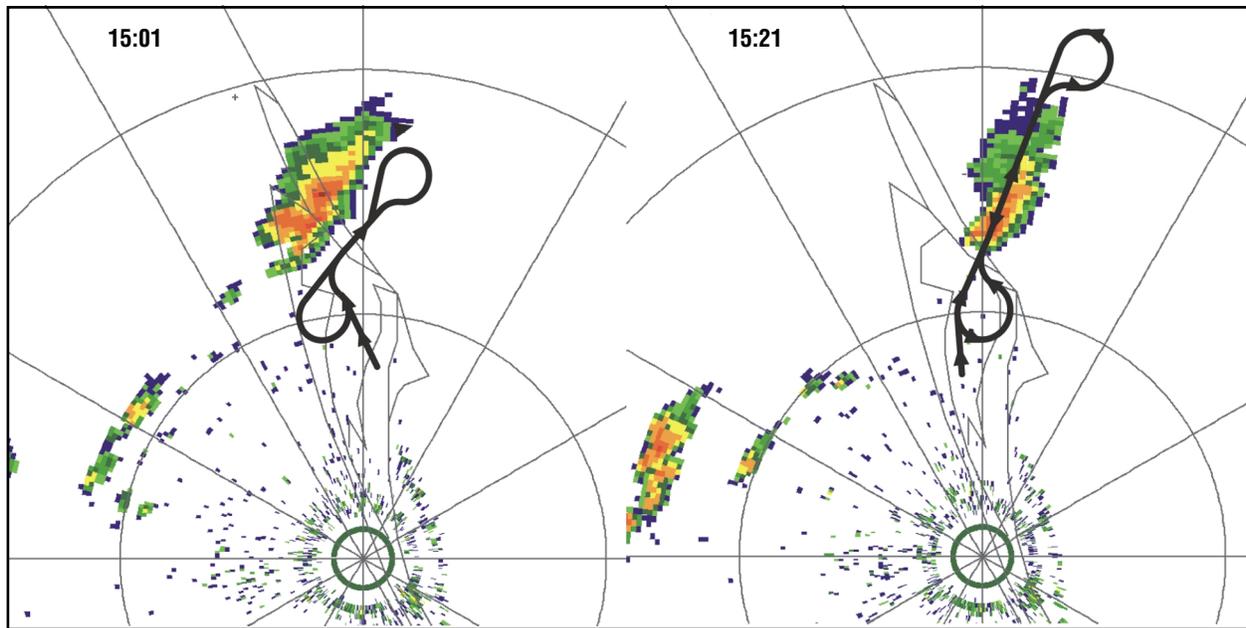


Figure 2.9.—Examples of WSR-88D radar images from the KSC area and possible ALTUS flight patterns over the KSC restricted area and ocean. Since the storm at 15:01 is too severe to overfly, the ALTUS will fly at a 5 km offset from the cloud.

Summer thunderstorms in the Huntsville, AL area are similar in size, behavior, and duration to those that develop at KSC (see Section 2.3.2). The climatological number of thunderstorm days for the Huntsville area is 8.5 days for June, 11.0 days for July, and 8.8 days for August. This means that on average, there will be thunderstorms every 3–4 days. However, the atmospheric instability and associated thunderstorms often cluster in time.

The primary disadvantage to operation from RSA is the lack of a range with restricted airspace away from population centers. For this reason, RSA may prove programmatically unacceptable at this time.

2.3.5 Mission Constraints

The primary constraint on the location of the field campaign is the availability of associated ground-based meteorological and thunderstorm instrumentation. Specifically, high-altitude measurements from the UAV are to be used in correlation with the very best ground-based systems available, and thus, the field campaigns must be made in relatively close proximity to such ground instrumentation sites. Because of this constraint, the project is limited to just a few locations throughout the country. An optimal site is located at KSC in Florida with operation being conducted out of the NASA hangar at

PAFB airfield. A second acceptable site from a scientific/weather standpoint is the RSA Army airfield in Huntsville, AL identified above. However, as discussed, the lack of a large restricted airspace at RSA may make this site less suitable at this time for the UAV demonstration program.

2.3.6 Low Level of Risk

The ACES flight program is low risk. There is little development risk since the ACES payload already exists and has successfully flown on the ALTUS. We propose to fly the ALTUS in restricted airspace at KSC to further reduce the risk to people or property on the ground. The aircraft is not being asked to perform beyond its proven capabilities nor will it be intentionally placed in hazardous situations (e.g., see discussion in Sections 3.3.2, 3.4.6, and 3.4.7). From a schedule and budget standpoint ACES is considered low risk as well, because of a conservative schedule slack and fidelity of cost estimates. Also, IDEA and GA-ASI are firm fixed price contracts and are experienced with the ACES payload.

2.3.7 Mission Success Metrics

ACES will be deemed successful by demonstrating the capabilities of UAV aircraft to engage in productive scientific storm research and by the publication of science results in peer-reviewed literature.

2.4 Baseline System

2.4.1 UAV Platform

The ALTUS UAV system consists of one ALTUS aircraft, one Ground Control Station (GCS), one Ground Data Terminal (GDT), and Ground Support Equipment (GSE). A typical setup is illustrated in Figure 2.10. Presently ALTUS can operate at a maximum range of approximately 125 n mi. This poses no limitation for the proposed Florida (or an Alabama) deployment since we would like to remain within 200 km of the center of the ground-based network. A C-band Line-of-Sight (LOS) data link provides two uplink and two downlink data streams to establish full duplex communication between the ALTUS aircraft and the GCS. Normally, one uplink and two downlinks are utilized. Figure 2.11 gives additional specifications of the ALTUS aircraft and system.

(a) Payload Capabilities. The ALTUS aircraft is a high-technology aircraft designed to perform high-altitude research missions. The internal payload capacity of the aircraft is located in the forward fuselage. The aircraft is capable of carrying any research payloads that fit within the weight (330 lbs.) and volumetric capacity of the aircraft or, alternatively, mounted externally on wing/fuselage stations. A custom, high-profile front payload bay cover can be fabricated to accommodate the larger volume internal payloads. Payloads are controlled using

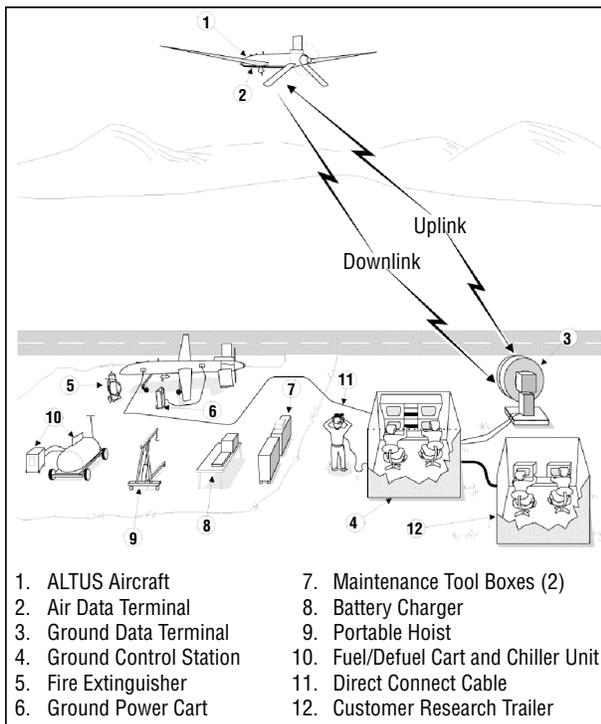


Figure 2.10.—Overview of the ALTUS system.

either a dedicated data link provided by the PI team or the ALTUS C-band LOS data link. Integration details are coordinated with the PI team.

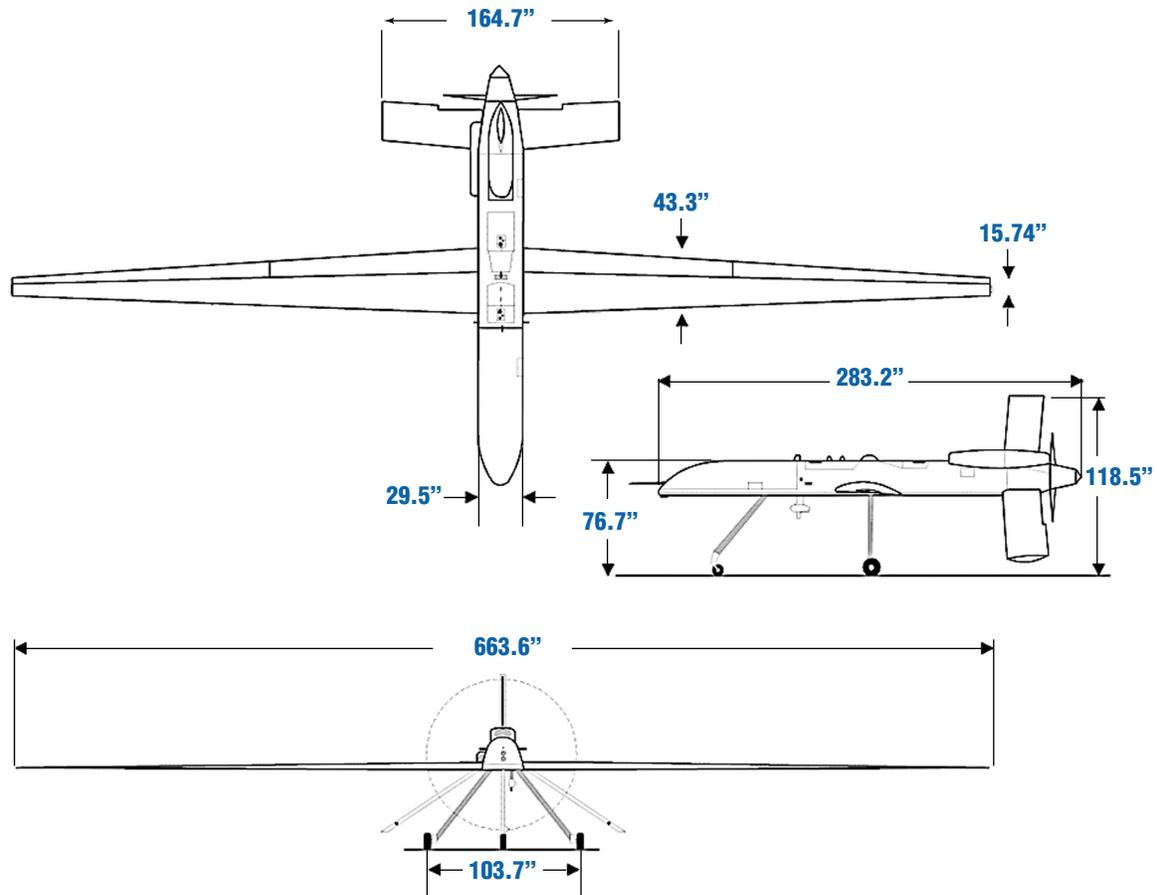
The ALTUS aircraft accommodates research payloads on a “plug-and-play” basis. Mechanical interfaces are accommodated by mounting payload components onto a composite tray that is attached to the aircraft structure. The aircraft composite structure is easily modified to accommodate payload access to the environment (hatches, ducts, windows, etc.). Electrical interfaces are Electronic Industries Association (EIA) standard RS-422. The payload and control console RS-422 interface is a full duplex asynchronous serial bus capable of 9,600 baud uplink at a 100% duty cycle. The payload capacity and standard interface features of the ALTUS system mitigate payload integration tasks and schedule risks. The benefit is that the research/UAV flight team can concentrate on mission accomplishments versus aircraft system functions.

(b) Ability to Meet Scientific Requirements of Mission.

The ALTUS system is a high-altitude derivative of the successful Predator system and encompasses identical subsystems and technology. The primary difference is the ALTUS incorporates a larger wing and an altitude-optimized propulsion system. The ALTUS system has been deployed to Oklahoma; Monterey, CA; Hawaii; and many other sites in support of NASA Department of Energy (DOE)/Atmospheric Radiation Measurement (ARM) and the Naval Postgraduate School scientific missions for oceanographic and atmospheric research. GA-ASI is the only company that successfully operates UAVs for science missions. To date GA-ASI has executed five major science missions in support of atmospheric research. GA-ASI is the only company that completed the 1999 Dryden Flight Research Center (DFRC) Government Performance Results Act (GPRA) milestone by demonstrating the capability to fly at 55,000 feet for 4 hour. GA-ASI is the only UAV system that completed the 1999 DFRC milestone of sustained flight above 50,000 feet for 8 hour. This makes ALTUS the most proven, tested, and “confirmed” high-altitude UAV system in existence.

2.4.2 Flight Instrumentation

This section describes the payload that will be flown on ALTUS in support of the scientific objectives discussed in Section 2.2. The proposed ACES payload has been developed under an SBIR activity with our IDEA, LLC subcontractor and managed by one of the Co-Is, Dr. R. Goldberg. It utilizes existing flight proven sensors from MSFC and GSFC, as well as a state-of-the-art data acquisition system developed under the SBIR activity.



Mission:	High-Altitude, Long-Endurance Flight. Scientific Research and Commercial Applications.
Dimensions:	Wing Span 55.3 ft; Wing Area 132 ft ² ; Length 23.6 ft; Height 9.8 ft.
Weights:	Empty 1,310 lb; Max fuel 550 lb; Max Payload Weight 400 lb; Max Takeoff Weight 2,150 lb.
Propulsion:	Rotax 914 Dual Turbo, Liquid Cooled, Four Cylinder. Displacement 74 in ³ ; Rated at 100 HP @ 52,000 ft.
Performance:	Max Altitude 55,000 ft; Endurance 4 hr (at 55K) 18 hr (at 30K); Max Speed 80 KTAS; Cruise/Loiter Speed 65 KTAS.
Payload Specs:	Size 58 in. L x 26 in. W (Adaptable for Specific Requirements—Approximately 18.6 ft ³); Normal Payload Weight 330lb; Max Weight 400 lb.
Termination Sys:	GA-ASI Rocket Deployed Parachute and NASA Flight Termination System.
Avionics:	GA-ASI PCM, C-Band Line-of-Sight RF; Adaptable for Over-the-Horizon Operations.
Payload Power:	800 W @ 55,000 ft; Up to 1.8 KW @ Altitudes less than 25,000 ft.
Navigation:	Litton LN-100G INS/GPS (P-Code GPS).
Landing Gear:	Normal Tricycle-Type Retractable Gear.
Max Op. Radius:	125 nmi
G Limits:	-2g to +4g

Figure 2.11.—More detailed specifications of the ALTUS UAV. The ALTUS is capable of carrying any research payloads that fit within the 330 lbs. weight and volumetric capacity of the aircraft.

Furthermore, this payload was successfully integrated and flown on the ALTUS UAV in September 2000. Only slight modifications and upgrades will be made to the sensors and the installation for this proposal.

The ACES payload includes several sensitive electrical, magnetic, and optical sensors optimized to remotely sense the lightning activity and the electrical environment within and around thunderstorms. Both the slowly varying and transient electrical and optical signals will be acquired. The summary of the scientific instrumentation is shown in Table 2.2. All the data will be recorded onboard using the advanced Flight Payload Data System (FPDS) developed for the ALTUS platform under the SBIR activity. In addition, during flights, selected instrument output will be sent to the ground via the UAV telemetry link enabling us to monitor target storms in real time. UAV video camera output will also help monitor storm conditions in real time. The volume, mass, and power of the proposed payload are well within the limits set by the UAV payload capabilities.

Figure 2.12 shows a picture of the ALTUS with the ACES payload fully integrated. The FPDS and several of the

instruments are labeled. The scientific sensors lie closest to the UAV nose, while the heavier 55 kg FPDS lies behind the suite, closer to the aircraft center of gravity. RFI sensitive sensors like the search coil and slow antenna were purposely placed closest to the nose, as far as possible from the ALTUS propulsion system located in the rear of the aircraft.

(a) Electric Field Mills. One of the most important measurements of thunderstorm development and severity is the “static” vector electric field produced by the storm. For this investigation we will install five state-of-the-art, low-noise, high-dynamic range electric field mills (EFMs) on the ALTUS. With these sensors, the full vector components of the atmospheric electric field (i.e., E_x , E_y , E_z) will be directly obtained, providing detailed information about the electrical structure within and around the storms overflown. Total lightning (i.e., CG and IC) is identified from the abrupt changes in the electric field data (e.g., see Figure 2.4). Additionally, it is often possible to differentiate between the IC and CG discharges. Storm electric currents can be derived using the electric field and the air conductivity measurements provided by the Gerdien conductivity probe.

Table 2.2.—Scientific instrumentation.

Sensor	Measurement	Performance	Power (W)	Mass (kg) ¹	Volume (cc) ¹	Temp; Pres. Range	Heritage
Electric field mills (5 sensors)	DC electric field: 3 axis	<10 Hz <1V/m–150kV/m	2.8	2.31	16,000	N/S	ER-2, ALTUS, other aircraft
Optical pulse sensor (OPS)	Optical lightning transients	320–1,100 nm	0.8	1.81	2,250	N/S	ER-2, ALTUS, ground based
Slow antenna	AC electric field	1Hz–100 kHz	3.0	1.81	7,500	N/S	ER-2, ALTUS, other aircraft, ground based
Gerdien conductivity probe	Conductivity	3×10^{-13} – 10^{-11} S/m	3.0	1.36	1,100	N/S	UAV (Navy Swallow), rockets
Search coil	AC magnetic field: 3 axis	100 Hz–100 kHz >1.3pT@10 kHz	0.3	0.91	1,650	N/S	Altus, swallow, numerous rockets
Magnetometer	DC magnetic field: 3 axis	0–100 Hz >10 nT	0.2	0.45	100	N/S	ALTUS
Accelerometer	Acceleration 3 axis	+/- 4G	0.1	0.45	55	-40 °/+85 °C	Aircraft, rockets
Flight payload data system (FPDS)	N/A	30 Ch@100 Hz ² 16 Ch@100 kHz ³	368	55 ⁴	156,000 ⁴	0 °/+50 °C 1 atm	ALTUS
Total			378	83⁵ (183 lb)	184,655 (6.8 cu. ft.)		

N/A: Not applicable

N/S: Instrument operation is not affected by predicted variations in temperature (-60 ° to +40 °C) and pressure (0.05 to 1 atm)

Notes:

¹ Includes sensor(s) and electronic boxes

² Continuous data collections

³ Triggered data collection

⁴ Includes power interface box

⁵ Includes all cabling and incidentals

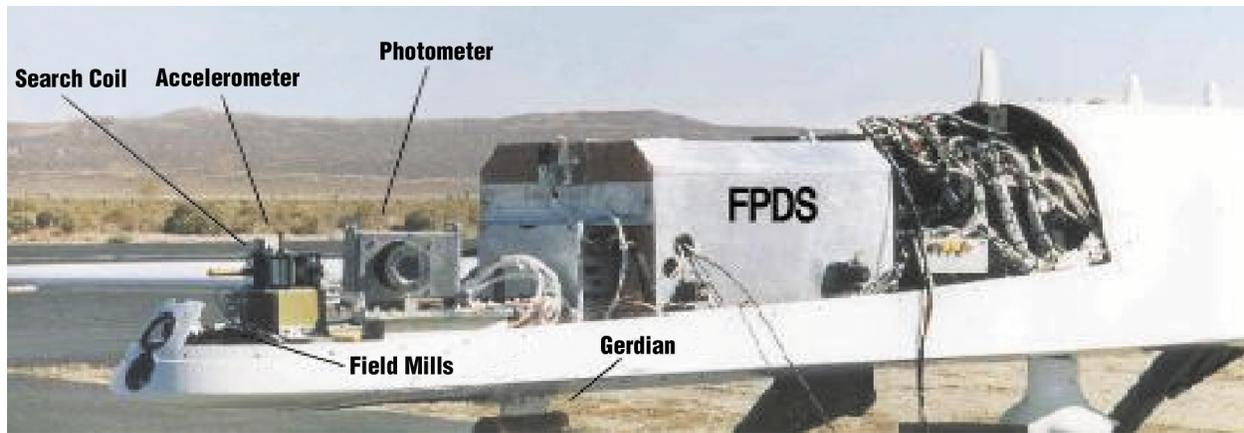


Figure 2.12.—ACES payload fully integrated with ALTUS, ready for first test flight on September 28, 2000.

The EFMs will measure the components of the electric field over a wide dynamic range extending from fair-weather electric fields (i.e., <1 V/m) to large thunderstorm fields (i.e., 150 kV/m)—a range of over five orders of magnitude. This wide dynamic range is needed to both sense the fair-weather electric field for calibration purposes and to determine the electric field vector in the region of a strong thunderstorm. The field mills also provide a measure of the electric charge (Q) on the aircraft. The EFMs incorporate self-calibration capabilities that will reduce the time required to obtain full aircraft calibration. In addition, with these mills the electric field signals are digitized at each mill and transmitted in a digital data stream, reducing signal noise and simplifying aircraft integration. The EFMs have relatively slow time response (~ 10 Hz) so it will not provide details associated with the fast transient electric field changes due to lightning.

During the SBIR flights in September, 2000 the EFMs helped establish that the ALTUS platform has very low electrical noise levels making it an ideal platform for conducting thunderstorm electrical observations (or for that matter, even fair-weather electrical measurements). Figure 2.13 shows fair-weather electric field measurements that were collected during calibration maneuvers on September 28, 2000. The ambient electric field is primarily vertical (E_z) and quite small, while the horizontal field, E_y is essentially zero. Nonetheless, it is easy to identify the small variations in E_y at 16:25 and 16:45 UTC that correspond to right and left roll maneuvers at 12 kft and 9 kft mean sea level (MSL), respectively. In addition, the EFMs can easily detect the increase in the fair-weather vertical electric field, E_z , as the ALTUS descends from 12 kft to 9 kft between 16:40 and 16:44 UTC.

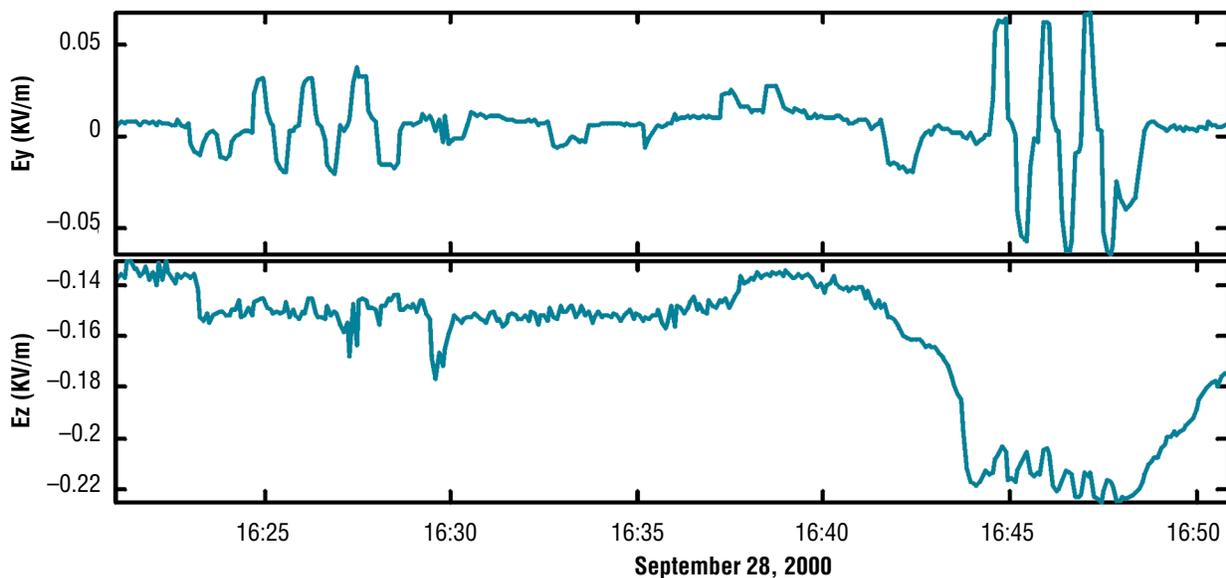


Figure 2.13.—ALTUS fair-weather electric field measurement that demonstrates the low electrical noise level of this aircraft.

(b) Optical Pulse Sensor. Collecting optical energy and power statistics from the cloud-top emissions from lightning represents another important measurement priority in the proposed investigation. A multiple channel, calibrated, OPS (we will upgrade the existing single-channel sensor with one or more additional channels) will be used to determine the intensity, duration, and waveform characteristics of the different types of lightning discharges from thunderstorms. The OPS will be configured to detect lightning events in the visible and near-infrared portion of the spectrum. Each channel consists of a photodiode at the focus of a wide angle (60°) field-of-view lens. A narrow-band interference filter is placed in the front of the lens to restrict the measurement to a strong emission feature in the lightning spectrum. The OPS will have no problem detecting transient lightning events during daytime conditions. The OPS is designed so that rapidly varying signals due to lightning are passed while slowly varying signals, such as sunlight reflecting off of the clouds, are strongly attenuated.

(c) Slow Antenna. The slow antenna (electric field change meter or electric monopole) is included in the UAV instrument suite to more precisely measure the transient electrical signals due to lightning. The slow antenna consists of a detector plate connected to a charge amplifier circuit with a decay constant of 0.1 s. The decay constant is set so that the DC and slowly varying components of the electric field are strongly attenuated at the charge amplifier output. The primary use of the slow antenna is to measure the electric field transients associated with lightning events (i.e., return strokes, leaders, k-changes, etc.). The slow antenna data will complement both the optical and the EFM data in identifying lightning discharges and in distinguishing IC from CG flashes. These data will be used in close conjunction with the ground-based LDAR and NLDN data sets.

(c) Conductivity Probe. The atmospheric conductivity measurements will be made by a Gerdien condenser probe with the ability to sense both positive and negative ion conductivities. The probe utilizes a concentric, cylindrical electrode geometry with the inner and outer electrodes serving as the collector/guard and return electrodes, respectively. The ion conductivity is determined by applying a voltage (V) that is swept linearly between the two electrodes over a 1-minute period, and measuring the resulting current (I). The slope of the I - V characteristic (dI/dV) provides the conductivity measurement. Special construction techniques are used at the collector input to reduce stray leakage currents and susceptibility to electromagnetic interference (EMI).

The Pennsylvania State University Gerdien condenser has flown previously on the Navy Swallow UAV. The radii of the inner and outer electrodes are 1.6 cm and 3.8 cm, respectively. The length of the collector is 6.4 cm. The inner electrode extends another 10 cm as a guard section that is used to mechanically support the center electrode and the inner electrode is recessed 3.8 cm from the leading edge of the outer cylinder. The whole assembly has a length of 20 cm and a mass of 0.286 kg. It is mounted via a 7.6 cm sidestrut to the underside of the aircraft. A separate electronics box (7.6 cm \times 5 cm \times 2.5 cm) contains the sweep and data amplifier electronics.

(e) Search Coils. The magnetic field antennas for this mission are three orthogonal search coil magnetometers, each consisting of many turns of fine wire wound about a high-permeability core, along with preamplifier circuitry. This instrument is specifically designed to measure AC magnetic fields in the frequency range of 100 Hz–20 kHz. Such search coils have been successfully deployed by GSFC/LEP on rocket (Norwegian PULSAUR and Sporadic-E Layer) and UAV (Naval Research Laboratory's Swallow) platforms in addition to use in ground-based campaigns (SPRITE 96).

The search coil measures $d\mathbf{B}/dt$, or temporal changes in magnetic flux density, which couples to the instrument in two distinct ways. The intended mechanism is transformer coupling, whereby AC field lines from a distant source couple to the windings of the sensor. The secondary mechanism is generator coupling, whereby the sensor is physically displaced within a DC magnetic field (e.g. the geomagnetic field). This mode will produce interference on a small aerial vehicle as it operates in turbulent air. In order to discern transformer/generator emission types, a vector accelerometer will be mounted in close proximity to the search coil. As such, physical displacement data will be recorded and used as a correlation parameter, along with DC magnetic field data, during data analysis. In addition, this technique provides a cross-calibration mechanism for AC and DC magnetic field sensors.

Figure 2.14 shows a frequency-time spectrogram from the search coil, which is very sensitive to electric currents, taken during one of the ACES flights at El Mirage. Over much of the frequency range, the search coil data are free of interference. The dominant source of noise, from the ALTUS engine spark plugs, is observed in a band-limited region below about 20 kHz, is periodic in nature, and is relatively weak (<90 mV out of a 10V dynamic

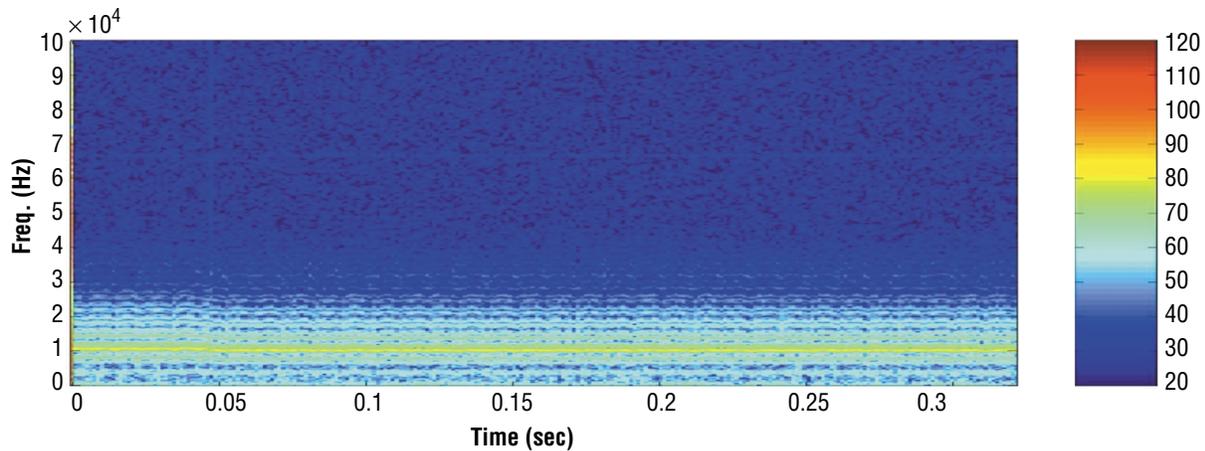


Figure 2.14.—High-resolution search coil dynamic spectrum (100 kHz \times 300 msec) taken during the September 28, 2000 test flight shows a low level of RFI.

range). The sensor did not saturate, and RFI is only a moderate component of the overall signal, further confirming that ALTUS can easily make these measurements.

(f) Magnetometer. The three-axis magnetometer is a highly-sensitive, high-resolution, three-axis fluxgate magnetometer designed for deployment on aircraft for in situ measurements of magnetic fields due to locally driven currents and other perturbations. The magnetometer not only senses the steady component of the Earth’s field, but also measures very low frequency magnetic fields. The instrument will measure changes in the ambient magnetic field during thunderstorm activities ranging from 0–100 Hz. Three analog output voltages will be interpreted to determine the vector magnetic field at magnitudes in the range of one milligauss to one gauss. A miniature three-axis fluxgate magnetometer, model APS533 by Applied Physics Systems, has been selected for this application.

(g) Flight Payload Data System. The FPDS has been built specifically for the ALTUS UAV under the SBIR activity previously mentioned. The FPDS is designed for the ingestion, digitization, and archival of the sensor and payload data. The FPDS uses a modular, VXI bus-base architecture, which gives it flexibility to adapt to various scientific payloads. In addition, the FPDS provides a variety of ground control (via command uplink) command capabilities controlling power (on/off and redundant source) and trigger functions. The FPDS will also be able to transmit small amounts of data to the ground during flights to allow the user to monitor select sensor output, as well as the health of all the instrumentation in real time. The transmitter/receiver system between the UAV and ground utilizes a 9,600-baud (i.e., low bandwidth) connection; therefore, the amount of data

transmitted during a mission will be limited. The FPDS has an external Ethernet port to effect fast download of the data after the plane lands.

For the proposed storm mission, the FPDS will include a medium-speed digitizer/frame grabber that will record the fast transient response from the sensors (i.e., slow antenna, search coil, OPS). The data from this frame grabber is continuously stored in a buffer until a trigger signal determines that an event should be stored. The data will be time stamped with Global Positioning System (GPS) timing and stored on hard disk and the system will be reset to collect the next event. There will also be a slow-speed digitizer that will continuously download data to the hard drive (i.e., field mills, conductivity probe, magnetometer). The slow-speed digitizer does not depend on a trigger event to occur, and will therefore record data for the duration of the UAV flight. The FPDS will also continuously ingest the digitized output of the electric field mills. The GPS will be used to time-tag the data with Universally Coordinated Time (UTC). This time will also be used to name the corresponding data files.

During a mission, measurements from the onboard electric field mills will be downloaded and monitored in real time to avoid areas of high electric field that might induce a lightning strike to the ALTUS.

2.4.3 Ground-Based Instrumentation

Since weather (especially thunderstorms) has such a significant impact on launch operations, ground processing operations in preparation for launch, and personnel safety at KSC, a large suite of weather sensors has been assembled and deployed to meet the operational forecast requirements. Observations include: (a) Total lightning from the LDAR and a 31-station electric field mill

network at KSC, (b) CG lightning from the NLDN and a local system, (c) radar data from the Melbourne WSR-88D and PAFB WSR-74C, (d) precipitation from a large rain gauge network (co-located at field mill sites) and (d) other meteorological data (i.e., winds, temperature, humidity, etc.). Table 2.3 summarizes the ground-based instrumentation available at KSC. We will augment these observations with GOES imagery and other satellite data as needed/available.

As previously noted, this data will be available to the ACES project in real time to assist in mission planning and flight operations. In addition, we plan to use a LISDAD display system to display lightning, radar reflectivity, and other meteorological parameters in real time, allowing storms of interest to be located and tracked in real time. Also, ACES will take advantage of the expertise, weather briefings, and other operational support provided by the 45th Weather Squadron (45 WS) that oversees the meteorological support functions at KSC and PAFB. Finally, the archival of many of these data sets is already occurring at the NSSTC Global Hydrology Resource Center (GHRC), or other locations, further reducing costs borne by ACES.

Table 2.3.—List of local weather sensors used by 45 WS. Except for WSR-74C all this data is saved and is available for climatological study. Routine external data sources are not listed, such as GOES/POES, NCEP products, etc. (Roeder, 2000).

Sensor	Number	Comments
Boundary Layer		
Weather towers	44	30 × 40 Km area, 2 to 150 m, wind, temperature, humidity
915 MHz Doppler Radar Wind Profiler/RASS	5	Wind (0.12–3 Km), 5 min virtual temperature (0.12–2.5 Km), 15 min
Surface observer	2	KSC (contractor), Patrick AFB (USAF)
Rain gauges	33	Most colocated at LPLWS
Upper Air		
RAOB	1	Asynoptic release times
Jimsphere	1	High precision wind balloon (only during countdowns)
Rocketsonde	1	20-90 Km, limited launches
50 MHz DRWP	1	Winds (2.0-19.0 Km), 112 gates (150 m spacing), 5 min refresh rate
Lightning		
LDAR	7	Detects all lightning types, depicts 3-D structure
Electric field mill network aka.: Launch pad lightning warning system (LPLWS)	31	Detects surface electric field, detects all lightning types
CG Lightning Surveillance System (CGLSS)	6	Improved accuracy with combined technology (IMPACT) sensors
NLDN *	105	CG lightning from commercial data source
Radar		
WSR-74C/IRIS	1	5 Cm, 2.5 min volume scan, customized products
WSR-88D *	1	NWS/Melbourne

* Not a local weather sensor, but is included for its importance in operational research or for completeness.

2.5 Descope Options

The proposed mission has been designed with low cost, schedule, and technical risks. However, descope options have been identified to reduce cost should funding levels require it. The proposed mission is designed so that following the first campaign, should the science and demonstration components of this proposal be satisfactorily achieved, the second campaign could be descoped. The descope options are listed in Table 2.4.

We have proposed to conduct two field campaigns during this investigation. A descope (Option 1), providing significant cost savings, would be to eliminate the second field campaign. The science and demonstration objectives may be achieved by one campaign. The

Table 2.4.—Desclope options.

Option	Action	Science Impact	Cost Savings
1	Desclope one field campaign	Decreased measurement statistics	~\$1400K
2	Reduce the number of flight hours per campaign from 64 hour to 45–50 hour	Potential decreased measurement statistics	~\$75–100K

primary impact of this descope will be a decrease in the overall measurement statistics. By descopeing an entire campaign, the storm observations would essentially be reduced by half. In addition, we would lose the opportunity to improve upon and extend the measurements made in the first campaign.

A second descope (Option 2) would be to reduce the number of flight hours allocated during each campaign. We have proposed to conduct campaigns consisting of eight flights of up to 8-hours duration. In the descope scenario, shorter duration missions of 5–6 hours duration would be flown instead. There may be a science impact, similar to the descope of a campaign discussed above, if the shorter missions significantly reduce the storm observations obtained. However, we may find 5–6 hours duration missions are typical even if this descope option is not invoked. In that case, there would be no science impact. Also, through the contractual arrangement with GA–ASI we will only pay for the flight hours actually used.

2.6 Data Analysis, Archival, and Distribution Plan

A mission cannot be deemed successful unless the scientific results from the project are made available to the public. Data analysis, archival, and distribution are considered fundamental elements in this process. We have considerable prior experience with successful aircraft, ground, and space-based missions similar to the ACES project. We will apply the same procedures and steps employed in these successful research projects to ensure a successful completion of the ACES project.

2.6.1 Analysis Concept Relative to Mission Requirements

The mission requirements determine all aspects of data collection and analysis from design of the instruments to the publication of the research results. Although these requirements and objectives extend across a broad range, the data analysis approach is the same for each requirement. The fundamental goal is to produce a high-quality data set and analyses that will advance the understanding of lightning-storm relationships and the global electric circuit, contribute to the calibration of the LIS, and demonstrate the utility of using UAV in Earth science investigations. The following highlight the sequence of steps that will be taken with respect to data analysis, archival, and distribution to ensure that ACES achieves mission success.

(a) Sensor Calibration. The first task is to calibrate the flight instruments. Calibration is usually a two-stage

process. The first stage is to calibrate the instrument in the laboratory. The laboratory calibration is designed to document the relationship between the instrument output (usually in volts) and a known input. We determine both the actual relationship (slope and intercept) and the precision (standard deviations or standard errors) of the instrument output.

The second stage in calibration is to determine the effect of the aircraft frame on the calibration of certain sensors such as the EFMs. The aircraft executes a series of maneuvers in the fair-weather electric field to determine how the ALTUS aircraft distorts the external electric field.

(b) Data Acquisition. The full dynamic range of the instrument data will be recorded by the FPDS. Since all of the scientific data will be stored digitally, there will be no loss of quality in the recording process. The software used to record the data will be tested to ensure that it will faithfully record the data instruments outputs.

(c) Local Storage of Flight Data. Scientific data will be downloaded from ALTUS after every flight. This is the standard procedure from previous aircraft field programs (including the ALTUS pilot program). Since the permanent archive is usually not accessible from field sites, we will store the scientific data locally on CD. An original and backup CD copies will be produced.

(d) Onsite Data Review (Quality Assurance) in the Field. After each flight, the downloaded data will be reviewed to monitor the status of each scientific sensor. With the FPDS system used in the ACES program, real-time monitoring of the sensor systems will also be made during flights. Any problems or failures that are identified will be diagnosed and repaired. This local review of the scientific data is the standard procedure applied to all previous aircraft field programs. A mission and instrument summary will be e-mailed daily to the ACES data management group for archival and inclusion on the ACES Web site (see *Dissemination of Data and Results* below).

(e) Transfer of Data to Permanent Archive. Once the field deployment is over, the data will be transferred to the permanent archive. For past flight research projects we have used the Global Hydrology Resource Center (GHRC), the data management arm of the GHCC, as our permanent archive location. We will continue to use the GHRC as the archive for ACES data and software (flight and instrument summaries, science data, documentation, and supporting data set read software) since the infrastructure of hardware, software, and personnel are already in place from the previous projects. These projects range

from multi-year satellite missions such as the LIS Science Computing Facility (SCF) to smaller-scale field programs such as the Convection And Moisture Experiments (CAMEX). Production of the flight summaries, data discussion, and development of individual data set read software will be the responsibility of the ACES science team, but the GHRC data-management personnel will coordinate management, ingest, archival, and distribution of this information. The quality-controlled ACES data sets will be publicly accessible through the GHRC ftp data server.

(f) Data Analysis. It is during the data analysis phase that the science requirements and objectives are directly addressed. Both a “case study” and statistical analysis approach will be used to address each aspect of the science objectives. It is anticipated that these analyses will serve to advance the understanding of lightning-storm relationships, improve the calibration of the LIS, and increase the understanding of the global electric circuit.

(g) Documentation. The GHRC will develop and maintain a descriptive campaign guide, instrument guides, data set guides, README files, and flight summaries files that provide comprehensive information about the project, instruments, and the data sets associated with each instrument. The GHRC will write these documents based upon input from the science team. Access to all the documentation will be available through the ACES Web site with direct links to the GHRC archive for data distribution. The GHRC will register all ACES data sets with NASA online data search and order systems including the Global Change Master Directory (GCMD), the EOS Data Gateway (EDG) and the local GHRC Hydrological Data Retrieval and Order (HyDRO) system. Registering the ACES data sets with the GCMD and EDG requires submitting metadata packets to the aforementioned systems.

Metadata describes the content of a data file. An everyday analogy is the nutrition and ingredients label on a food package. An ACES metadata packet will describe the “ingredients” (e.g., parameter, instrument, time, geospatial extent) and “nutrition” (e.g., data quality) of the data set. This requires the specification of various parameters and entry of information as required by each system. Each data set must have a Data Interchange Format (DIF) completed to qualify for inclusion in the GCMD. Entries into the EDG require the valid identification of geophysical parameters that match the type of data contained in the data set. These “valids” must be identified by the data center and submitted to the EDG staff at NASA GSFC for installation. For example, the

“valids” for an ACES data set might be “optical pulse”, “electric field”, “lightning”, “conductivity,” and other words or parameters that a user might enter while conducting an online search for data. The GHRC personnel will develop the metadata and valids and ensure their inclusion into the directories and catalogs. Thus a comprehensive metadata database combined with descriptive documentation will make the ACES data sets useful and available to the broader scientific community.

(h) Dissemination of Data and Results. The best way to advance the knowledge gained from the ACES program is by the publication of peer-reviewed research papers, informative articles, and an education and public outreach activity. This will ensure maximum scientific and public relations impact of the results of this program. Along with the scientific community impact, the dissemination of the ACES results will allow more popular outlets (e.g., general interest science Web sites and print media such as USA Today) to convey the benefits of the program to the general public.

An ACES Web site will host a complete description of the project. The Web site will describe the project’s goals and objectives and provide descriptive articles about the ALTUS aircraft, instruments, and science research. In addition, daily progress reports will be given while the field campaign is under way. The Web site will have links to ACES news articles on the popular Web site Science@NASA, as well as links to ACES data and ancillary data sets (e.g., NEXRAD radar, and ground-based lightning networks) archived at the GHRC and other sites (e.g., GSFC and KSC).

An education outreach (Section 5.3) is planned that will make use of actual ACES data sets to develop school lesson plans to convey the excitement of scientific research by allowing students to explore the mission decision-making process.

2.6.2 Quality Assurance Approach

Scientific and operational quality assured data is essential for mission success. We have adopted a two-fold strategy to obtain and maintain science quality. First, by following the steps outlined in Section 2.6.1, the highest scientific quality data sets will be acquired. Through careful calibration, field examination, and detailed analyses the degree of the data quality (precision, errors, and standard deviation) can be established and documented. Quantifying the data quality is important because even when data are found to have problems, they can still remain extremely useful in data analyses if the level of the data quality is known.

Second, operational quality assurance will be achieved by applying configuration management principles and ISO 9000 techniques that are currently utilized at GHRC. Science algorithms, production software, and documentation are placed under Unix RCS version control. Output products will be reviewed for file integrity and consistency. Data and products backed up onto the archive volumes will be written with a verification option that ensures that the file quality is maintained.

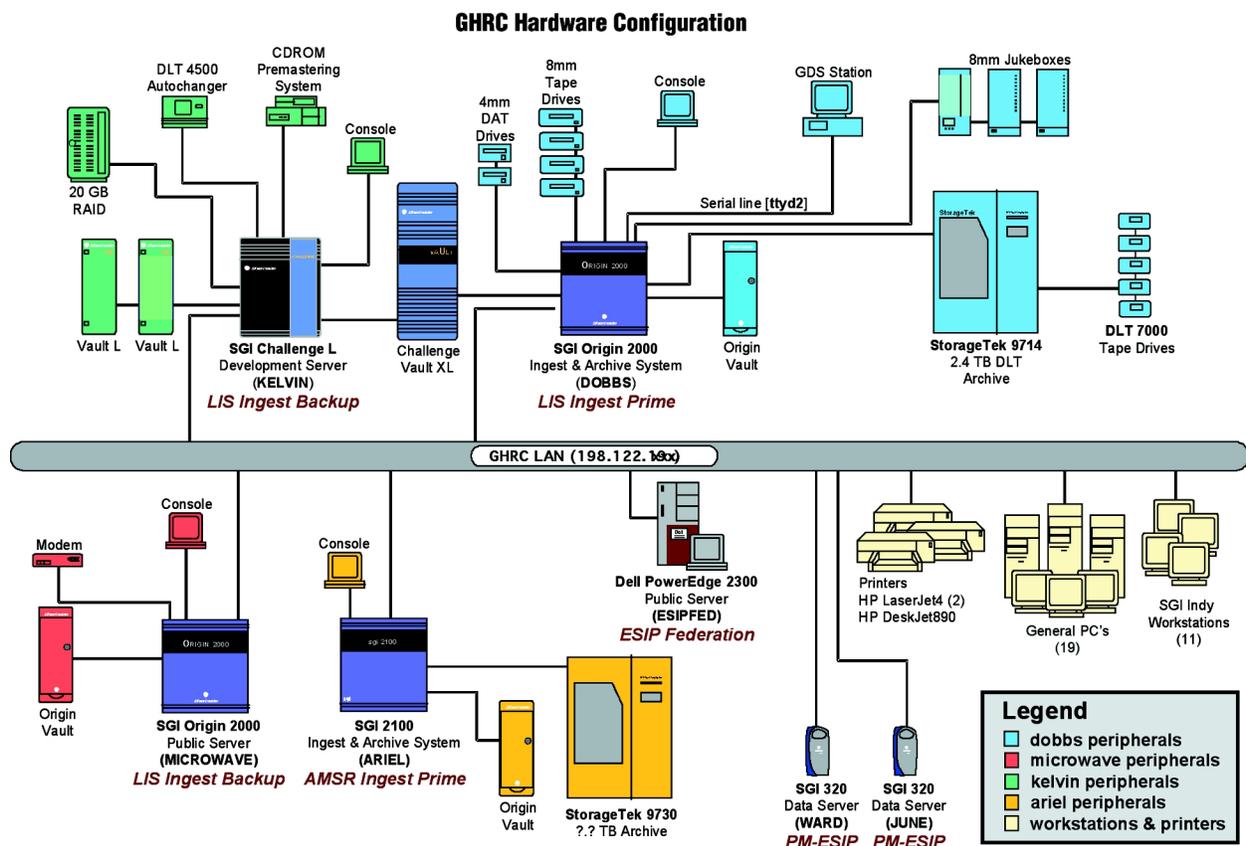
2.6.3 Facility Needs

Our data analysis and archival facility needs are modest. Since the data will be transferred to CD immediately after each flight, additional infield storage capacity will not be needed. During the analysis stage of the project, processing and storage capabilities will leverage off of the existing computer and archival facilities at the GHRC illustrated in Figure 2.15. No major computer equipment purchases will be needed for analysis and storage. ACES will utilize the computing power of the LIS ingest and

archive system (SGI Origin 2000, machine name “DOBBS”) with the attached StorageTek 9714 robotic archive. We will procure the necessary disk space to ensure sufficient online storage for the low-volume, continuous data products (e.g., EFMs, conductivity, aircraft navigation, etc.) and the associated browse products. Public access to the online products and archive retrievals will be through the public server (SGI Origin, machine name “MICROWAVE”). Additional media (DLT tapes) for archiving all the ACES data sets (triggered data, continuous, and derived products) on the StorageTek 9714 will also be purchased.

2.6.4 User Interface and Archival Plan

Flight and instrument summaries, data and products, documentation, and supporting software will be archived and distributed by the GHRC. Co-located with the science team, the GHRC provides a full spectrum of data management services from data ingest and archival, to processing and distribution. The GHRC data-management personnel



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Figure 2.15.—GHRC hardware configuration displaying the file servers, computer servers, storage devices, and various peripherals.

will coordinate archival and distribution of this information, as well as advertising through NASA search and order systems and a project Web site.

Preliminary and “quick-look” results will be made available to all researchers in a timely manner. During the experiment, we will produce examples of data that show or suggest important findings since they will be of great interest to the experiment participants, NASA program managers, Earth science community, and the science attentive public. The GHRC will provide a Web-based calendar display system and file management capabilities developed for such quick-look information. The web calendar, with links to the data sets, browse images,

documentation, and ancillary data and browse products (e.g. GOES images and NEXRAD radar) provides an intuitive user interface to access the ACES products and results.

ACES data collected in the field will be archived immediately after the completion of the field campaign to ensure data safety and integrity. Derived products generated by the science team will be archived at the GHRC within 6 months of the completion of the field campaigns. The GHRC will use the commercial AMASS™ file management system and Oracle™ database to administer the data sets across multiple computer platforms and storage devices.